AD-A042 190 AVCO LYCOMING ENGINE GROUP STRATFORD CONN STRATFORD DIV F/G 5/1
INVESTIGATION OF FACTORS CONTROLLING ENGINE SCHEDULED OVERHAUL --ETC(U)
MAY 77 P A KING, R L GIVENS DAAJ02-75-C-0018
UNCLASSIFIED LYC-76-42 USAAMRDL-TR-77-9 NL

1 OF 2
AD
A042190

AD A042190

USAAMRDL-TR-77-9

12

INVESTIGATION OF FACTORS CONTROLLING ENGINE SCHEDULED OVERHAUL - T53/T55

Avco Lycoming Engine Group
Stratford Division
Stratford, Conn. 06497

May 1977

Approved for public release;
distribution unlimited.

Prepared for

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
Fort Eustis, Va. 23604

EUSTIS DIRECTORATE POSITION STATEMENT

The principal objective of this program was to develop an improved understanding of those factors that influence the establishment and management of turboshaft engine scheduled overhaul intervals. The analyses presented herein are considered to be reasonable and can form the basis for critical assessments of the need for scheduled time-between-overhauls (TBO) for turboshaft engines. In addition, this report provides a limited analysis of the potential to operate turboshaft engines without a scheduled overhaul. Therefore, it is recommended that this report be used to help define or revise current inventory and new development turboshaft engine maintenance requirements. This program represents one effort under this Directorate's continuing assessment of helicopter components to develop data essential for implementation of the Department of Defense concept of "Reliability Centered Maintenance."

Donald Artis, Robert Campbell, and Victor Welner served as project engineers for this effort.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*)

(19) REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
(18) 1. REPORT NUMBER USAAMRDL-TR-77-9	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
(6) 4. TITLE (*and Subtitle*) INVESTIGATION OF FACTORS CONTROLLING ENGINE SCHEDULED OVERHAUL – T53/T55		5. TYPE OF REPORT & PERIOD COVERED
		(14) 6. PERFORMING ORG. REPORT NUMBER LYC-76-42
(10) 7. AUTHOR(s) Paul A. King Robert L. Givens		(15) 8. CONTRACT OR GRANT NUMBER(s) DAAJ02-75-C-0018 new
9. PERFORMING ORGANIZATION NAME AND ADDRESS Avco Lycoming Engine Group, Stratford Division Stratford, Connecticut 06497		(16) 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62209A 1F262209AH76 (17) 00 040 EK
11. CONTROLLING OFFICE NAME AND ADDRESS Eustis Directorate U.S. Army Air Mobility Research and Development Laboratory Fort Eustis, Virginia 23604		12. REPORT DATE (11) May 1977
		13. NUMBER OF PAGES 183
14. MONITORING AGENCY NAME & ADDRESS(*if different from Controlling Office*) (12) 181 p.		15. SECURITY CLASS. (*of this report*) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A

16. DISTRIBUTION STATEMENT (*of this Report*)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (*of the abstract entered in Block 20, if different from Report*)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*)

Turbine Engine	Time-Between-Overhaul (TBO)	Maintenance
Overhaul Intervals	Design	Reliability
Helicopter	Depot Returns	

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

This report presents an analysis of the factors responsible for the return of helicopter turbine engines to depot.

Engine component causes are detailed from the larger set of total system-caused returns. The derived data are used to identify significant parameters which can allow the design of high initial time-between-overhauls with an optimum growth rate. Models and examples of the design approach are presented with emphasis on reliability and maintainability support. The report is concluded with a qualitative analysis of advanced component system concepts and their probable effect on TBO interval and safety/mission reliability.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*)

409 974

SUMMARY

The various causes for the return of gas turbine engines to depot for maintenance are examined in this investigation. The sample selected for review and analysis of historical data include T53 and T55 models in both military and commercial deployment. The time span of the historical data studied allows a comparison between military combat versus military peacetime and military versus commercial overhaul experience. Section 1.0 discusses depot return rates relative to design and environmental stresses.

The concept of a composite engine was introduced to provide an average value for comparative purposes. The reasons for depot return of specific engines are compared with those of the composite engine. Special emphasis is placed on engine component-caused depot returns and their relationship to design parameters.

Section 2.0 presents recommendations for procedures and criteria that, through the design processes, can control the TBO or durability return rate. The process uses the composite engine critical component subsystem listing derived in Section 2.0. Failure mode and hazard-rate analyses from previous designs are used to estimate the probabilities of component/subsystems meeting the system requirement. The process is iterative, and the understanding of the relationship between design margins and depot returns will improve. Analysis of new designs will indicate the risk associated with achieving a specified time-between-overhauls (TBO) interval. The analysis may indicate a specific design and use relationship that would warrant an on-condition or condition-monitoring approach to depot return.

Section 3.0 lists and describes advanced component and system concepts. A qualitative analysis is made as to their probable effect on TBO interval, flight safety, and mission reliability.

PREFACE

The investigation described herein was conducted by the Avco Lycoming Engine Group, Stratford Division, to review and analyze the factors controlling engine scheduled overhaul intervals. The program was sponsored by the Eustis Directorate of the U. S. Army Air Mobility Research and Development Laboratory (USAAMRDL), Fort Eustis, Virginia, under Contract DAAJ02-75-C-0018.

The program was technically supervised by T. House, V. Welner, R. Campbell, and D. Artis of USAAMRDL.

The principal investigators for this study were P. King and R. Givens. W. Lobdell, Director, and S. Wallace, Manager of the Avco Lycoming Reliability and Maintainability group, had overall responsibility for program management.

The contributions of the Engineering, Stress, Design and Product Support departments of Avco Lycoming Engine Group are appreciated by the authors.

TABLE OF CONTENTS

	Page
SUMMARY	3
PREFACE	5
LIST OF ILLUSTRATIONS	10
LIST OF TABLES	14
INTRODUCTION	16
1.0 REVIEW AND ANALYSIS OF HISTORICAL DATA	20
Source and Selection of Data	20
Selected Engine Returns	20
Description of Selected Engines	21
Depot Return Categories	23
Composite Engine Description	24
Depot Return Categories (Composite Engine)	24
Depot Return Summaries	27
T53-L-11A/11B Engines	27
T55-L-7B/C Engines	27
T53-L-13A Engines	30
T53-L-13B Engines	30
T5311 and T5313 Engines	33
Mean-Time-Between-Depot-Returns (MTBD): (T53/T55 Engines)	33
Scheduled Engine Returns	35
Unscheduled Necessary Environment-Caused Returns	36
Foreign Object Damage	36
Erosion	42
Maintenance Errors	43
Additional Environment-Caused Returns	47
Unscheduled Necessary Engine Component-Caused Returns	49
Returns Caused by Mainshaft Seal Failures	51
Returns Caused by Bearing Failures	67
T55 Engine Bearing Problems	77
Compressor Rotor Problems	78
Fifth-Stage Compressor Disc	86
Air Diffuser	86
Turbine Blades	86
Power Turbine Oil Impeller	88

TABLE OF CONTENTS (Continued)

Page

Fuel Control Drive Spline Wear 88
Review of Extended-Service-Life Testing 89
Review of Engine-Caused Returns 93
Oil Leaks and Consumption 93
Review of Engine/System Diagnostics 95
Spectrometric Oil Analysis 95
Chip Detectors 105
Turbine Engine Parameter Sensors, Monitors, and Fault-Warning Devices - General 108
Safety-of-Flight 109
Comparison of Depot Returns - All Causes for Different Engine Applications 110
Military Peacetime Operation Versus Military Wartime Operations 110
Commercial Returns Versus Military Engine Returns 112
Established TBO and Inspection Periods 114
Unscheduled Unnecessary Returns - Defect Not Substantiated 115
Unscheduled, Convenience Returns 117

2.0 CONCLUSIONS AND RECOMMENDATIONS 119

Conclusions 119
Recommendations 121
Testing Recommendations 122
Bearing and Seal Component Rig Tests 122
Engine Testing 123
Endurance Testing 123
Mission Duty Cycle Testing 123
Low-Cycle Fatigue 124
Design Reliability Plan 126
Example of Design Reliability Analysis 131
Component Evaluation 133
System TBO Interval Probabilities 137

3.0 EVALUATION OF ADVANCED DEVELOPMENT CONCEPTS 149

Aerothermodynamic Components 149
Compressor 149

TABLE OF CONTENTS (Continued

	Page
Axial Compressor Materials	150
Centrifugal Compressor	151
Compressor Reliability Assessment	151
Turbine	152
Turbine Discs	153
Turbine Blades	153
Turbine Reliability Assessment	153
Power Management	154
Ceramic Components	154
Bearings	155
Seals	156
Gears and Clutches	157
Bearings, Seals, and Gears - Reliability Assessment	157
Lubrication System	158
REFERENCES	159
APPENDIX A - BASIC DATA	160
APPENDIX B - T53-L-13B ACTUARIAL ANALYSIS	175
APPENDIX C - MAINTENANCE ALLOCATION CHARTS	176
APPENDIX D - FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS (FMECA)	179
APPENDIX E - ESTIMATING WEIBULL PARAMETERS FOR COMPONENT FAILURE MODES	180
APPENDIX F - STRESS-STRENGTH METHOD COMPONENT ANALYSIS	182

LIST OF ILLUSTRATIONS

Figure		Page
1	Engine Return Categories	16
2	Composite Engine Depot Returns	25
3	Summary of Depot Returns, T53-L-11A/11B Engines	28
4	Summary of Depot Returns, T55-L-7B/C Engines	29
5	Summary of Depot Returns, T53-L-13A Engines	31
6	Summary of Depot Returns, T53-L-13B Engines	32
7	Summary of Depot Returns, T5311 and T5313 Commercial Engines	34
8	Depot Returns Comparison, Military Versus Commercial	35
9	T53 Turboshaft MTBD Engine-Caused Returns	36
10	TBO Growth for T53-L-11, T53-L-13, and T55-L-7	37
11	Composite Engine, Environment-Caused Returns	39
12	FOD Screen and Particle Separator	40
13	T53 Turboshaft Engines Worldwide MTBD Resulting from FOD	41
14	Modified First-Generation Sand and Dust Separator Incorporating Self-Cleaning Feature (Ejector Nozzle)	44
15	T53 Turboshaft Engines MTBD - Erosion	45
16	Centrifugal Compressor Housing Flame-Spray Repair	46
17	Power Shaft Flame-Spray Repair	47

LIST OF ILLUSTRATIONS (Continued

Figure		Page
18	Composite Engine - Engine-Caused Returns	50
19	T53-L-11 Number 2 Bearing Package	60
20	Number 1 Double-Row Segmented Positive-Contact Pressurized Seal	61
21	Number 1 Bearing Face Seal Installation	62
22	T53-L-13 Number 2 Bearing Package Schematic	63
23	Number 2 Seal for Improved Scavenging Airflow Sawcut Seal Design	64
24	Typical Number 2 Bearing Package Airflow Versus Shaft Speed	65
25	Number 2 Bearing Face Seal Installation	66
26	Weibull Plot - Number 2 Forward Seal	68
27	Weibull Plot - Number 1 Seal	69
28	Weibull Plot - Number 21 Bearing	71
29	MTBD for T53 Number 2 Bearing Cage Failures	75
30	Typical T53-L-13 Compressor Rotor After Failure of the Fourth-Stage Disc..................	80
31	Front Overall View of a Fourth-Stage Compressor Disc Which Sustained Failure of a Single Tenon	81
32	Fracture Surface of a Typical Tenon Which Was Completely Severed	81
33	Fracture Surface of a Typical Tenon Which Sustained Separation of Only Its Forward Position	82
34	Typical Cracked Tenon	82

LIST OF ILLUSTRATIONS (Continued)

Figure		Page
35	Weibull Plot of Compressor Fourth-Stage Aluminum Disc	83
36	Centrifugal Impeller Showing Vane Damage	84
37	Centrifugal Compressor Fatigue Life	87
38	Sun Gear Retaining Bolt and Power Shaft Installation	89
39	T55 Improved Reliability and Service Life Test Cycle	92
40	Composite Unscheduled, Necessary Engine-Caused Symptomatic Inspection Returns	94
41	SOAP Returns or Candidates - Causes Found, T55 Engines (1 April 1975 Through 31 December 1975)	98
42	SOAP Engine Returns - Causes Found (1 January 1972 Through 31 December 1976)	101
43	TBO Growth of T53 Commercial Engines (Rotary Wing Application)	116
44	Initial TBO (Production Engine) Versus Test Hours	125
45	The Bathtub Curve	127
46	Percentage of Engines Returned to Depot Due to Age - T53-L-13B	127
47	Data Feedback System Flow Diagram	129
48	Failure Data Analysis Flow Path	130
49	Analysis Flow Path for TBO Interval Design	132
50	Engine Duty Cycle for Example Analysis	133

LIST OF ILLUSTRATIONS (Continued)

Figure		Page
51	Average Mission for the UH-1H	135
52	Equivalent Engine System Block Diagram and Math Model	136
53	System Block Diagram and Math Model	138
A-1	T53-L-11A/11B Basic Data	161
A-2	T55-L-7 Basic Data	162
A-3	T53-L-13A Basic Data	163
A-4	T53-L-13B Basic Data	164
A-5	Commercial Basic Data	165

LIST OF TABLES

Table		Page
1	Unscheduled Necessary Environment-Caused Returns - All Engines	38
2	Additional Environment-Caused Returns	48
3	Composite Engine-Caused Returns	52
4	Unscheduled Engine Component-Caused Depot Returns	54
5	Number 1 Seal Failures	55
6	Number 2 Forward Seal Failures	56
7	Number 2 Aft Seal Failures	57
8	Number 3 Seal Failures	58
9	MTBF of Mainshaft Bearing	70
10	Comparison of T55-L-7 Field Experience and Extended-Service-Life Test	91
11	Engine Symptomatic and Inspection-Caused Returns	95
12	SOAP Engines Returned to Depot (1 January 1972 Through 31 March 1973)	96
13	SOAP Candidate Engines Shipped to Depot (1 April 1975 Through 31 December 1975)	100
14	T53-L-13B Engine Returns Reviewed for Numbers 1 and 21 Bearing Failures - SOAP - Chip Detectors	102
15	T53-L-13B SOAP Samples - Oil Contamination (1973)	104
16	Discrepancies Found as a Result of Chip Detector Activation	106

LIST OF TABLES (Continued)

Table		Page
17	Chip-Detector-Found Engine Failure Identified by Cause Component	107
18	T53-L-11A/11B Engine Returns - Vietnam Versus Other Locations (1 January 1967 Through 30 June 1968)	111
19	Engine Returns - Defects Not Substantiated	117
20	Parts Not Field Replaceable, Causing Depot Returns	139
21	Field Replaceable Parts With Failure Modes Causing Depot Returns	143
A-1	Depot Return Rates of All Engines Per Million Operating Hours	166
A-2	Summary Matrix Composite Engine - All Engines	169
A-3	Summary Matrix Composite Engine - All Military	171
A-4	Summary Matrix Composite Engine - Commercial	173

INTRODUCTION

The frequency of engines being returned to depot is considered to be a prime driver of engine life-cycle costs. The total rate of return is usually a combination of unscheduled returns and a fixed-schedule overhaul interval or time-between-overhauls (TBO). It is desirable to fix the scheduled overhaul interval as high as possible, within the constraints of mission reliability and flight safety, in order to minimize life-cycle costs. Unscheduled necessary returns to depot are separated into two causal categories: (1) engine component caused, and (2) operational environmental caused. Both causes are related to and influenced by engine system design.

The precipitation of an engine-caused depot return event is usually symptomatic. Therefore, the decision as to the necessity of returning an engine requires preliminary diagnostics and fault isolation to establish the level of maintenance that is required. The accepted practice, to minimize maintenance costs, is to perform maintenance at the lowest echelon practical. Violations of this practice occur in the form of unnecessary and convenience-type returns to depot.

The returns of engines to depot are categorized in Figure 1. The six categories of returns appearing on the data sheets are:

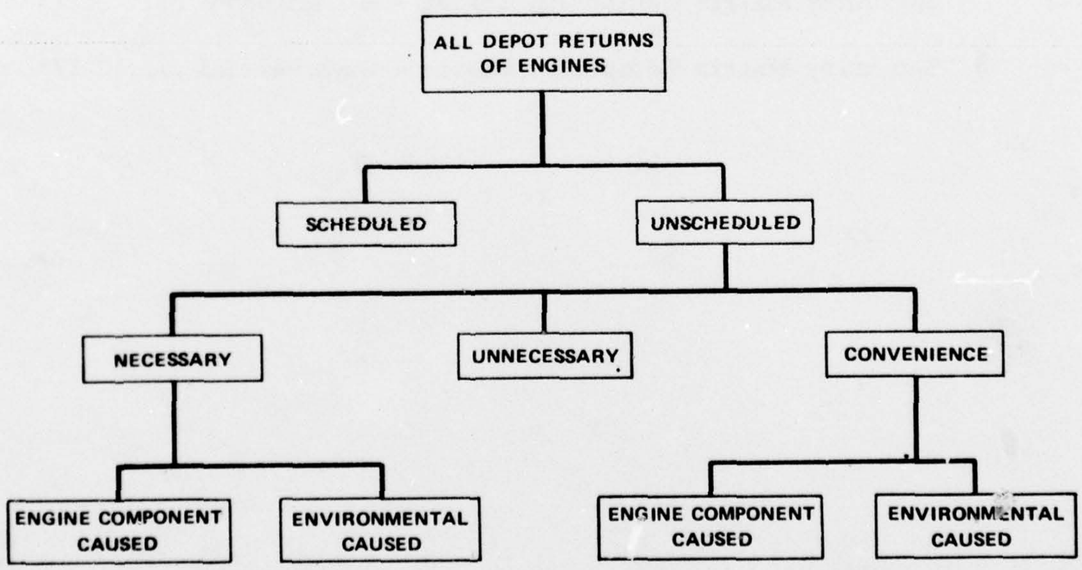


Figure 1. Engine Return Categories

1. Scheduled
2. Unscheduled, necessary engine component caused
3. Unscheduled, necessary environmental caused
4. Unscheduled, unnecessary
5. Unscheduled, convenience engine component caused
6. Unscheduled, convenience, environmental caused.

A scheduled return identifies an engine that is returned to depot as part of a planned activity; the most common reason is the achievement of the TBO interval. Other scheduled returns could be associated with airframe returns to depot or special investigations.

Unscheduled returns are randomly distributed events that are caused by the engine or its components and the environment in which the engine operates. Unscheduled returns can also be caused by events categorized as unnecessary, or a convenience to the using organization.

Necessary returns are those events that require the engine to be returned to depot for corrective maintenance.

Unnecessary returns to depot are those returns for which the reason for return could not be verified or because there was no immediate need for corrective or preventative maintenance at depot level.

Convenience returns are returns to depot of engines that could have received corrective maintenance in the field, but for reasons of logistics, strategy, etc., they were returned to depot.

The data sample sets were selected to afford a broad view of depot-return causes for a variety of engine models, operating conditions, and deployment environments. The data sets also provided component information sufficient to support the Weibull analysis and time failure-rate studies for specific failure modes. The selected sample sets, containing a total of 9004 returns, are:

Model	Time Span	Environment	No. Returns Analyzed	Operating Hours
T55-L-7, B, C	CY 1969	Military	844	512, 406
T53-L-13B	CY 1973	Military	1061	869, 291
T53-L-11	CY 1968	Military	2618	1, 250, 000
T53-L-13A	CY 1970	Military	3851	1, 700, 000
T5311 A & B*	1965-1975	Commercial	630	1, 136, 911
T5313 A & B*	1965-1975	Commercial		

*These are commercial model designations of the T53-L-11 and T53-L-13 engines.

Data from the sets were analyzed to provide insight as to what causes and reasons were the "drivers" of depot returns for each set. The results were used for comparative set analysis in terms of percentages and frequencies. Data sets were then summed to provide percentages and frequencies of an average of a composite engine.

Additional investigation was made into the areas of engine component failure modes, and where possible, Weibull plots were made to determine the relationship between failure frequency and operating time. Failure effects were noted, and safety and mission impacting failure modes were identified. The presence and effect of diagnostics on the depot returns are also discussed. The latter part of Section 1.0 attempts to relate earlier design and testing criteria to the failures that caused depot returns.

The analysis presented in Section 1.0 is used as the basis in preparing recommendations and procedures for controlling the factors that determine overhaul intervals. It is recommended that engine TBO capability be a primary design consideration and included as a system requirement. The composite engine evaluated in Section 1.0 is the first of an iterative process that continually refines the relationship between failures that cause depot returns, design selection, and system parameters. Data included in Section 1.0 strongly indicates that depot returns can be greatly reduced by directing design-configuration to environmental-use relationships, rather than redesigning the engine components. The area of convenience-type returns is one that may be driven by circumstances beyond the immediate control of the operating command. However, the exercising of this prerogative may be somewhat engine-design related through decisions that hinge on ease of maintenance. Unnecessary returns are considered to be operating-system caused and, when grouped with convenience returns, will be considered as exogenous variables and not within the control plan discussed in Section 2.0.

The statistical approach to meeting system requirements for maximum TBO and failure related engine life centers on depot-return failure sensitive parts. These parts with their failure modes and frequencies have been identified in Section 1.0. Probabilities are computed for failure modes using frequencies and distributions estimated in Section 1.0. The combined probabilities result in a probability for the engine TBO interval and the risk associated with mission and safety returns for the complete engine. It is expected that continued use of the procedures relating component design margins to depot returns will result in increased overhaul intervals, reducing unscheduled return frequencies, and eventually using on-condition and condition monitoring maintenance and overhaul plans.

The possible effects of advanced components or systems on TBO intervals, flight safety, and mission reliability-impacting depot returns is qualitatively explored in Section 3.0.

1.0 REVIEW AND ANALYSIS OF HISTORICAL DATA

SOURCE AND SELECTION OF DATA

Over 40,000 T53 and T55 engines were returned for depot action during the past 10 years. Records for these returns are on file in a data bank at the Avco Lycoming Engine Group, Stratford. These records formed the source of the historical data from which approximately 9,000 returns were selected for a detailed review.

These returns were not selected at random but chosen according to peak utilization periods (in flying hours), to obtain a cross section of engine models. After the engine model was selected, the returns for the year that had the most activity were then studied. However, a bias in failure frequency was introduced in some areas in order to investigate a wider range of failure modes. For example, the T53-L-13A CY 1970 data was included because of compressor problems. The years of peak activity of these models are discussed below.

Selected Engine Returns

Period	Model	Returns and Hours
CY 1968	T53-L-11A/11B	2,618 Returns 1,250,000 Flying Hours

This model year was selected since it was a peak utilization year for the T53-L-11A/11B engine. This engine model represented the end of the first generation of T53 engines, and had accumulated 3,250,000 operating hours prior to 1968, mostly in utility-type helicopters (UH-1 Series). Military operations during this period were conducted under severe combat conditions in Vietnam.

Period	Model	Returns and Hours
CY 1969	T55-L-7B/7C	844 Returns 512,406 Flying Hours

T55 series engines were selected because they represented a different configuration and were installed in a heavy cargo helicopter (CH-47 Series). Again, 1969 represented a year of peak utilization in Vietnam. Like the T53-L-11, this engine also was the last of the first generation and had accumulated over 1,000,000 hours prior to 1969.

Period	Model	Returns and Hours
CY 1970	T53-L-13A	3,851 Returns 1,700,000 Flying Hours

The T53-L-13A model engine represents the first engine in the second generation of the T53 family. Horsepower had been increased from 1,100 in the T53-L-11B to 1,400 shaft horsepower in the T53-L-13A. Most of the hours flown were under combat conditions, with some of the engines being installed in AH-1G gunships, whose mission profiles and engine duty cycles were more severe than the UH-1 series aircraft.

Period	Model	Returns and Hours
CY 1973	T53-L-13B	1,061 Returns 869,291 Flying Hours

The T53-L-13B incorporated a titanium compressor rotor and other design improvements over the T53-L-13A. This period was selected to provide military peacetime operational data. These engines were installed in both UH-1 and AH-1G Series aircraft.

Period	Model	Returns and Hours
1965-1975	T5311 and T5313 Series Commercial	630 Returns 1,136,911 Flying Hours

These engines were selected in order to introduce commerical data into the study and, thus, provide a comparison between similar engines being operated in military and commercial environments. These engines, installed in Bell helicopter Model 205, were used in a wide variety of operations, from off-shore oil-rig resupply to forestry logging and crop dusting.

Description of Selected Engines

The T53-L-11 1,100 shaft horsepower turboshaft engine was delivered to the U.S. Army in August 1963. This turboshaft engine incorporated the following improvements over the T53-L-9 series. The acceleration air-bleed system was modified to a transient-type with characteristics that made the bleed system remain open during power transients in order to improve the acceleration from flight idle to takeoff. The Number 1 main bearing installation was modified to reduce vibration, an in-line fuel filter was added, the air diffuser was modified to increase surge margin, and the customer air-bleed takeoff port was relocated. Alternate and emergency fuel capability was obtained by using a scoopless combustor, modified T-cane fuel injectors, and two hot-streak igniter fuel nozzles.

The 1, 100 shaft horsepower turboshaft T53-L-11A engine introduced in January 1966 has one difference in addition to the T53-L-11 configuration. This engine used the improved K4 gearing with a 24-tooth small output spline.

The 1, 100 shaft horsepower turboshaft T53-L-11B engine was delivered to the U. S. Army in December 1966. This engine used the improved K4 gearing with large 26-tooth output spline for compatibility with the redesigned helicopter transmissions.

The 1, 400 shaft horsepower turboshaft T53-L-13 engine was delivered to the U. S. Army in August 1966. This turboshaft engine incorporated the following significant improvements. Transonic compressor blades were incorporated in the first two stages of the axial rotors to provide increased air mass flow and to obtain the 1, 400 shaft horsepower rating. Variable inlet guide vanes provided good compressor stage matching over a wide speed range along with excellent compressor stall margin. A two-stage gas producer turbine was used for increased turbine efficiency. A two-stage power turbine having higher efficiency was used to supply higher power to the output shaft. A new atomizing combustor design incorporated improved heat and corrosion-resistant alloys for longer life.

The 1, 400 shaft horsepower turboshaft T53-L-13, with delta (Δ) marked on the engine data plate, contained a glass-bead-peened 36-blade second-stage compressor disc. The glass peening provided the disc with improved stress-rupture properties prior to availability of the 34-bladed disc.

The 1, 400 shaft horsepower turboshaft T53-L-13A Suffix A engine has a 34-blade second-stage compressor disc incorporated into the basic T53-L-13 configuration. The Suffix A identifies this feature.

The 1, 400 shaft horsepower turboshaft T53-L-13A engine includes all of the following features:

- Improved Number 2 bearing seals
- Six-probe twelve-point thermocouple harness for greater accuracy
- Improved Number 2 bearing scavenge system
- The 34-blade second-stage compressor disc.

The 1,400 shaft horsepower turboshaft T53-L-13A Suffix A engine is a modified T53-L-13A engine with an improved fourth-stage compressor disc forging that had controlled flow lines and grain size.

The 1,400 shaft horsepower turboshaft T53-L-13B is the most advanced production engine in the T53 turboshaft series. This engine includes the following additional major improvements:

1. Titanium was used in the second - through fifth-stage compressor rotor discs for increased durability, resistance to stress corrosion, and improved low-cycle fatigue characteristics.

2. Compressor blades were retained with single-thickness locking plates.

3. Improved Number 2 bearing sawcut seals were incorporated for resistance to coking.

4. First- and second-stage gas producer turbine nozzles were cast for greater service life.

5. Expansion bolts connecting the centrifugal compressor housing to the air diffuser were used for improved clamping, which reduces the Number 2 bearings outer race rotation.

6. An improved sun gear thrust washer made from synthetic material was incorporated for better wear characteristics.

DEPOT RETURN CATEGORIES

After the previously discussed engine returns were selected, they were categorized into depot return groups. Each engine model was first categorized as being either a scheduled or an unscheduled return, where scheduled-return engines either achieved scheduled TBO or were returned as part of a special inspection program (see Figure 1).

Next, the unscheduled returns were subdivided into necessary, unnecessary (defect not substantiated), and convenience-type groups. Necessary returns were further divided into engine-caused or system-caused returns. Where engine-caused returns included those engines returned because of component problem, system-caused returns related to operational or environmental factors. Unnecessary-type returns (defect not substantiated) include those engines in which no defect could be found upon examination at the overhaul facility. Convenience-type returns include engines that could have been repaired in the field, but, due to various reasons, were returned for depot action.

The raw data from computer storage were tabulated, analyzed, and condensed, and the results are presented in Figures A-1 through A-5 (Appendix A). Although every effort was made to preserve the original reason for return, some consolidation was necessary in order to reduce the large volume of data into manageable categories.

COMPOSITE ENGINE DESCRIPTION

In order to broaden the view of the various causes for engine returns, a "composite engine" was created by summing all like-categories from each engine group. This composite engine allows comparison between each engine and the composite, as well as "military composite" versus "civil (commercial) composite". To a degree, then, the composite engine represents the normal engine and is used throughout the report as a reference even though it is heavily weighted by the T53-L-13A data.

DEPOT RETURN CATEGORIES (COMPOSITE ENGINE)

Figure 2 depicts the major categories of engine returns, as applied to the composite engine. These categories are described below:

Scheduled Engine Returns

These returns include engines that reached a TBO interval, which ranged as low as 600 hours for some engines and as high as 2,500 hours for others. It should be noted that only a 6.48 percent of all depot returns or 107 engines per million operating hours reached a TBO interval.

Unscheduled Necessary, Engine Component-Caused Returns

This category represents the next largest group at 18.39 percent or 303 engine returns per million hours. The chief causes found in the engines studied are:

1. Oil leakage and consumption due to mainshaft oil seals.
2. Oil contamination, caused by bearing problems.
3. Compressor component defects such as disc, blade, or vane failures.

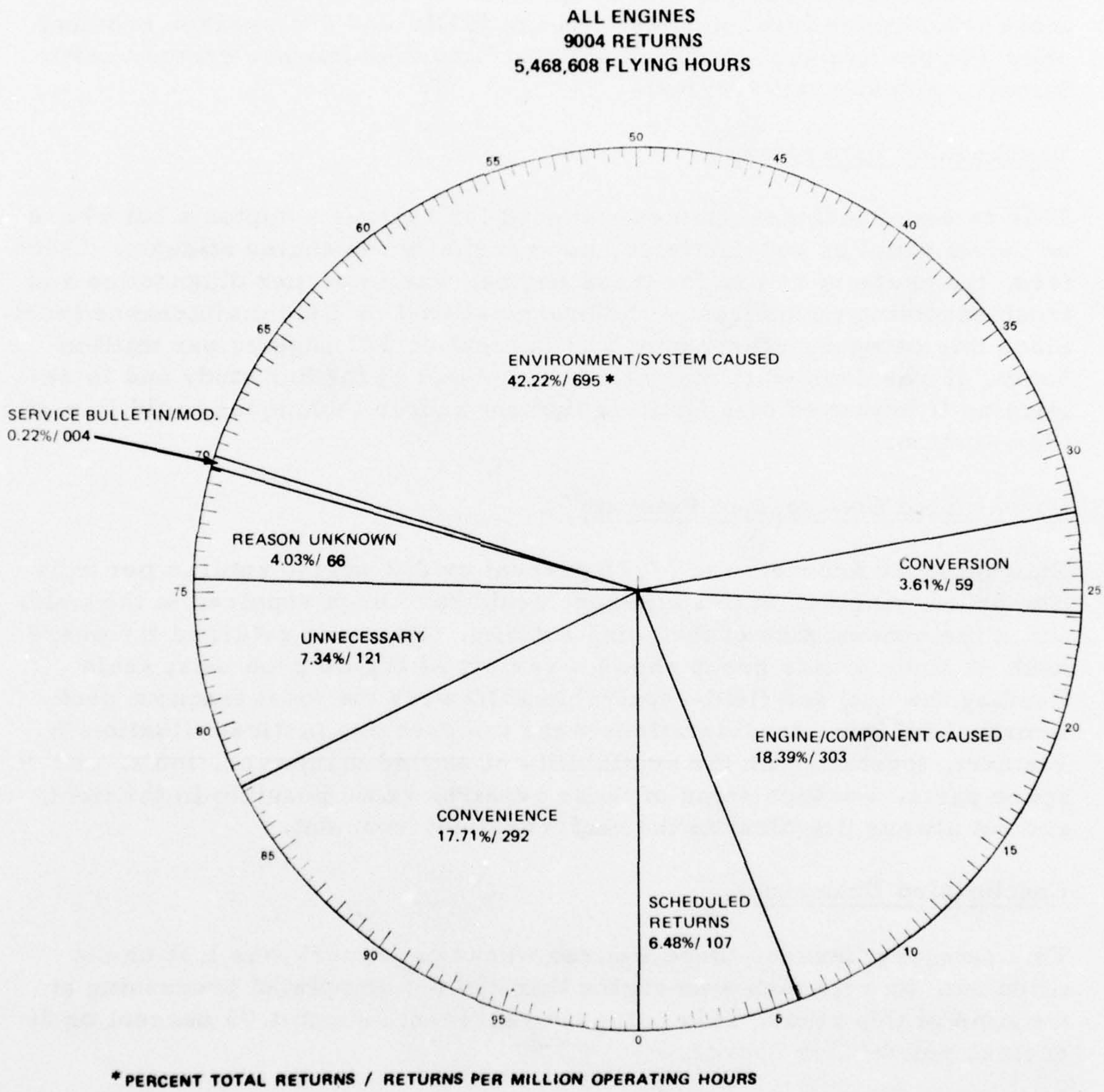


Figure 2. Composite Engine Depot Returns

Unscheduled Necessary, Environmental System-Caused Returns

This category represents the largest group, i.e., 42.22 percent or 695 engine returns per million operating hours. The principal reasons for these returns are foreign object damage (FOD) and compressor erosion; other factors are such items as operator and maintenance errors, battle damage, and aircraft accidents.

Unscheduled Unnecessary

This category includes engines returned for various symptoms but where no defect could be substantiated upon receipt of the engine at depot. Therefore, the cause of return for these engines was improper diagnostics and troubleshooting techniques at the organizational or field maintenance level. Since this category represents 7.34 percent or 121 engines per million hours, it was decided to make this the subject of further study and to determine if improved diagnostic equipment and/or techniques could improve the situation.

Unscheduled Convenience Returns

This category accounts for 17.71 percent or 292 engine returns per million hours. Engines in this category could have been repaired in the field, but at the convenience of the using activity, they were returned for overhaul. A study of this group shows a variety of engine problems; seals (leading the list) and field-repairable FOD were the most frequent problems. Additional considerations were the pressing tactical situation in Vietnam, together with the availability of skilled manpower, tools, and spare parts. Perhaps some of these repairs, while possible in the field, are not always practical in the real world environment.

Unscheduled Unknown

This category includes those engines whose paperwork was lost or not filled out, or represents an engine that had not completed processing at the time of this study. This category represents about 4.03 percent or 66 engines per million hours.

The remaining engines reviewed were returned for conversion to other models, for incorporation of service bulletins for modification work orders (MWO's), and they represent 3.61 percent or 59 per million hours. Figures 3 through 7 illustrate the categories representing the returns of each engine model selected for this investigation. Summaries of these activities are presented in chronological order. These summaries provide an overview of the principal causes of premature engine returns. For a detailed discussion of component problems, refer to "Unscheduled Necessary Engine/Component-Caused Returns".

DEPOT RETURN SUMMARIES

T53-L-11A/11B Engines

Figure 3 shows that 70 percent of the T53-L-11 engines returned to depot were due to environmental causes. FOD and erosion were the major factors, and the particle separator retrofit program initiated in 1967 was starting to take effect. See environment-caused returns on page 35. The scheduled return rate for this engine of 144 per million operating hours was higher than any other military type engine, and higher than the composite engine which included the commercial models. The T53-L-11A/11B was the last of the first generation engines and incorporated many design improvements over the earlier models. Consequently, the necessary engine-caused return rate ($274/10^6$ hour) is the lowest for all military models and lower than the composite engine.

T55-L-7B/7C Engines

The T55-L-7B/C has the highest unscheduled engine returns due to engine causes of the group studied (see Figure 4). A review of these causes shows that mainshaft seals lead the list, followed by bearings and air diffuser cracks. The Number 2 bearing and seal package is not field-replaceable on this engine. Again, the operational environment plays an important part, with over 40 percent of the returns (mostly due to FOD and erosion) indicating the need for environmental protection on the CH-47 type aircraft.

Unnecessary and convenience returns are close to the norm for the study groups. This engine had a scheduled return rate of $19/10^6$ hours, which is the lowest rate of all the engines studied.

Since the T55-L-7B/C incorporates several design improvements over the T55-L-5 series, one would expect a better showing; however, the basic difference between these models was improvements in the hot end and not the seal and bearing packages, which contributed so heavily to early returns.

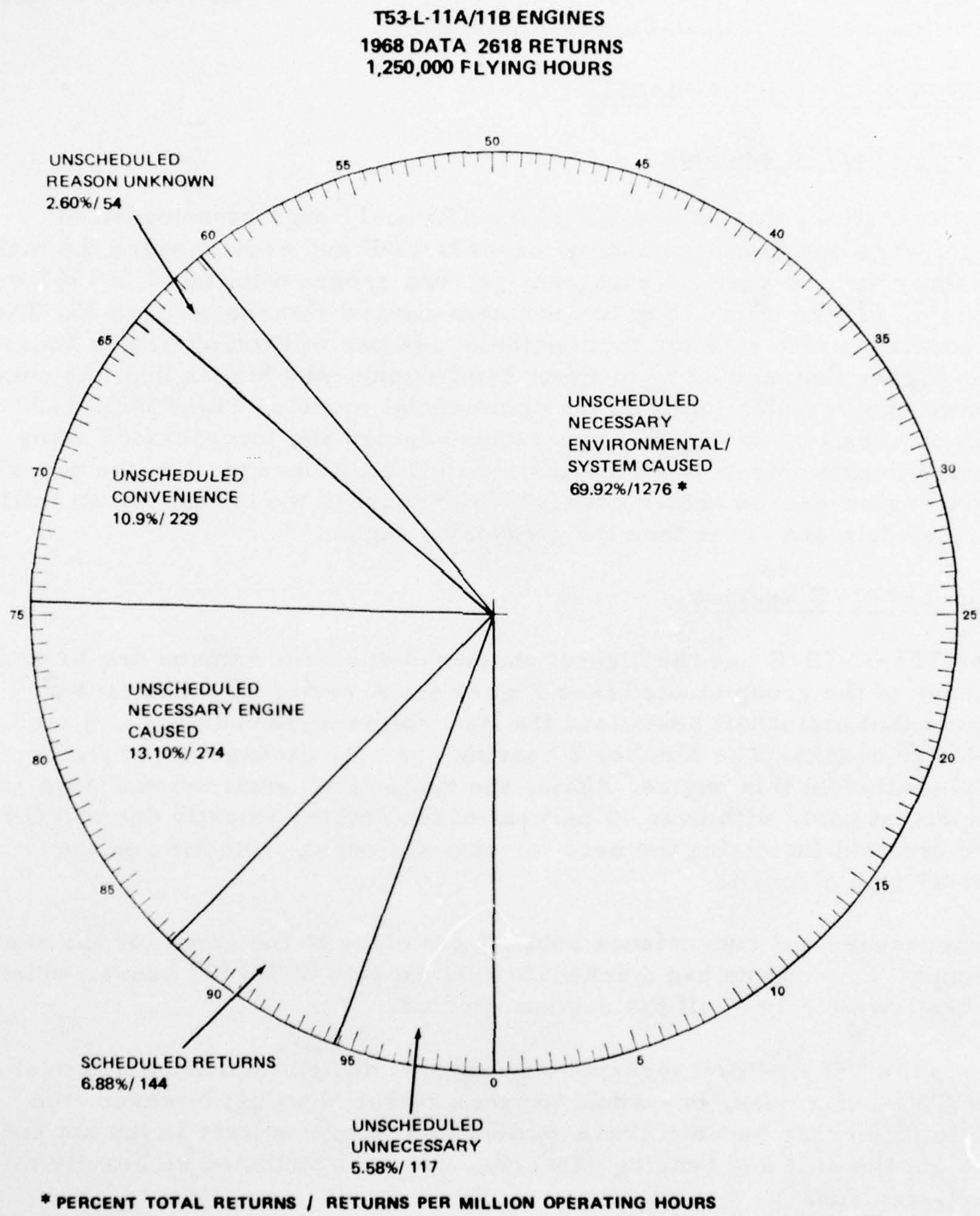


Figure 3. Summary of Depot Returns, T53-L-11A/11B Engines

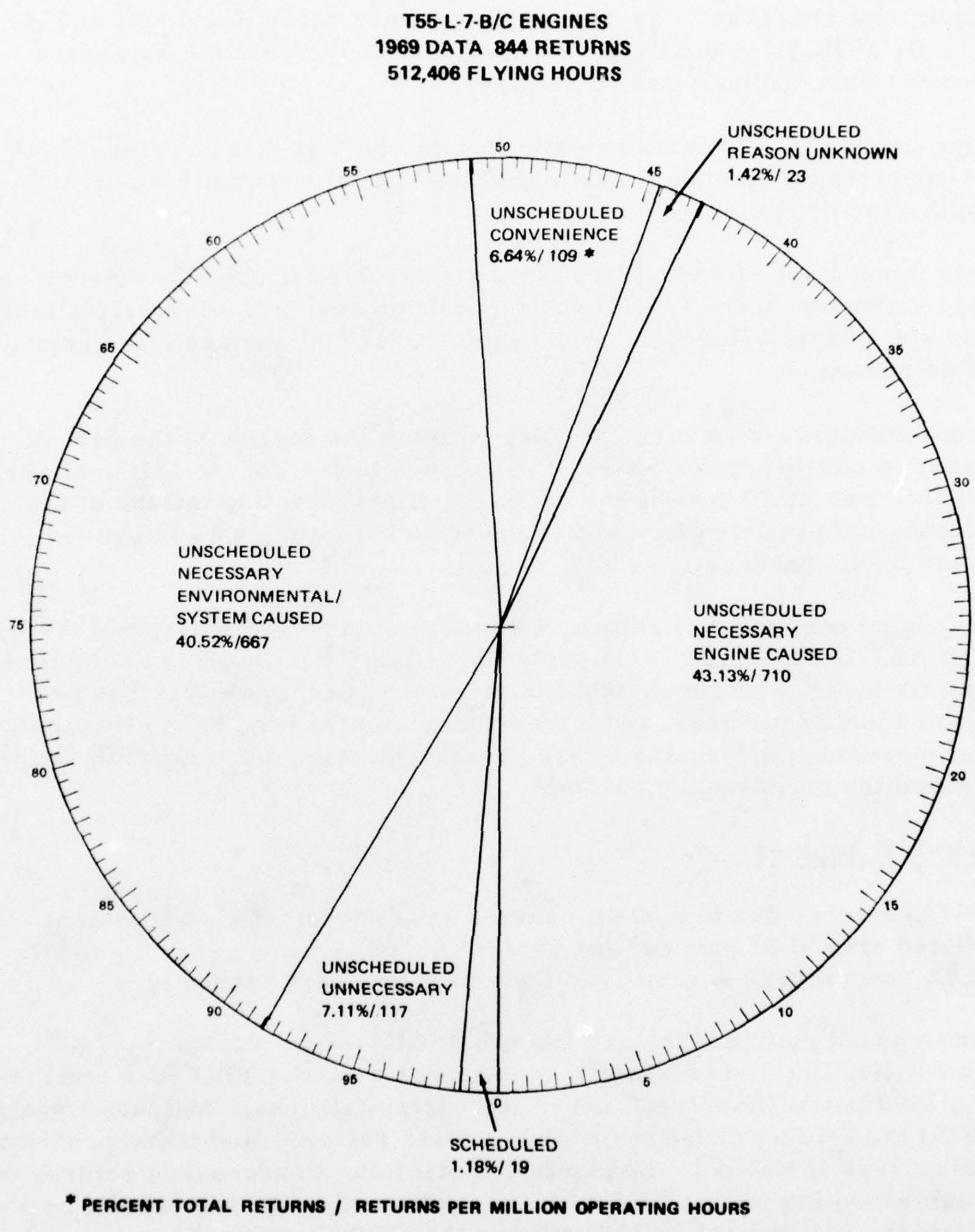


Figure 4. Summary of Depot Returns, T55-L-7B/C Engines

T53-L-13A Engines

A significant decrease in system-caused return rates is evident in Figure 5. By 1970, the benefits of the inlet screen and particle separator programs were beginning to be realized.

Engine-caused return rates are higher than the T53-L-11 series. Non-field-replaceable mainshaft seals lead the list, closely followed by compressor disc problems.

Higher speeds and temperatures were also factors in the convenience returns (engine-caused). The Number 2 position seal was adversely affected, and in spite of its being field replaceable, over 500 engines were returned for this reason.

The unscheduled conversion category reflects the desire on the part of the user to convert these T53-L-13A engines to the T53-L-13B configuration. This was motivated by the safety-of-flight affecting failure of the aluminum compressor discs and the need to incorporate an improved Number 2 seal package.

Unscheduled unnecessary return rates were somewhat higher than those for the T53-L-11 series. This probably reflects the increased complexity of this model with its variable inlet guide vanes, two-stage gas producer and power turbines, and a transonic compressor. These features, while improving performance, made troubleshooting more difficult and increased the maintenance burden.

T53-L-13B Engines

By 1973, returns due to system causes, operations, and environment stabilized around 37 percent and $453/10^6$ hours. These were due mostly to FOD, even though screens had been installed (see Figure 6).

Engine-caused return rates are lower ($301/10^6$ hours versus $349/10^6$ hours for the T53-L-13A), while at the same time the TBO rose from 600 to 1800 hours (now 2,400 hours for certain engines). Mainshaft seals are still the leading cause for engine-caused returns, and these problems are discussed in detail in the component section. Unnecessary returns due to troubleshooting were also lower, probably reflecting the peacetime maintenance procedures in 1973 versus the 1970 Vietnam data.

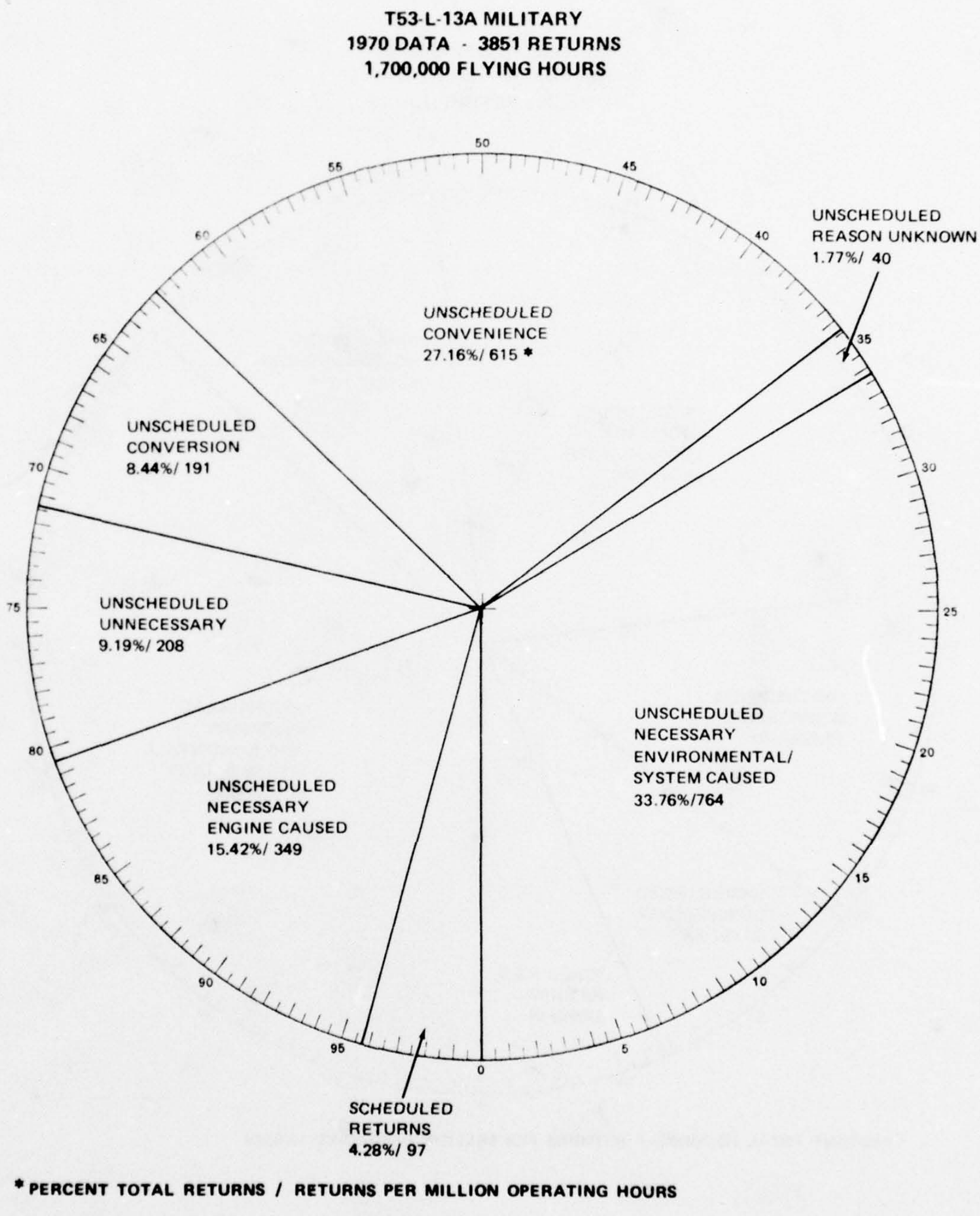


Figure 5. Summary of Depot Returns, T53-L-13A Engines

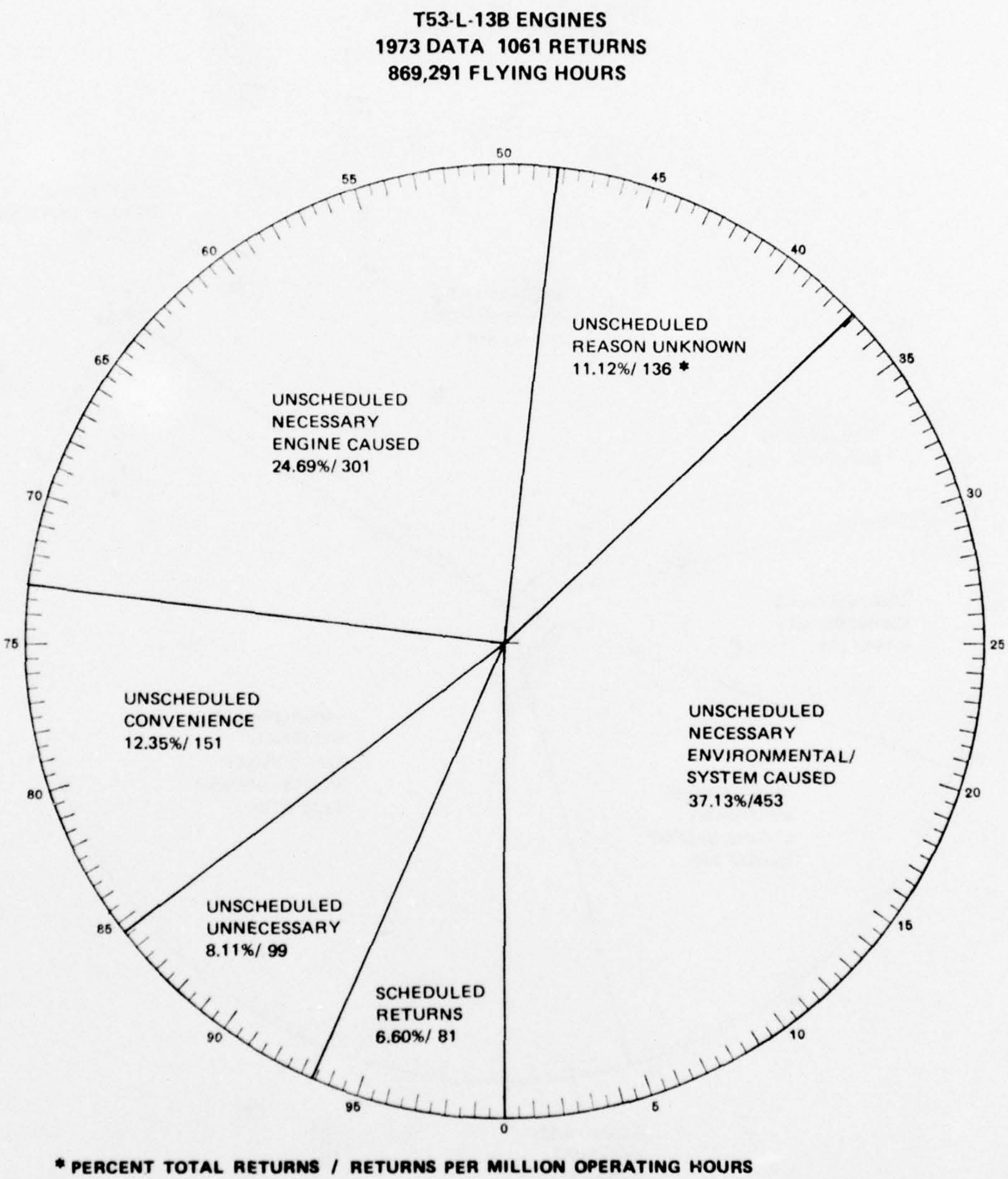


Figure 6. Summary of Depot Returns, T53-L-13B Engines

The rate of engines reaching TBO was $81/10^6$ hours, down slightly from the T53-L-13A. However, as mentioned earlier, the TBO interval had tripled. Therefore, the T53-L-13B is more durable than the T53-L-13A. It is also more durable than its lower-powered predecessor, the T53-L-11B engine, which has a rate of $144/10^6$ hours, in a 1, 200-hour scheduled return interval.

T5311 and T5313 Engines

Unscheduled system, i. e., operation and environment, return rates are much lower for the commercial engines studied $150/10^6$ hours versus $453/10^6$ hours for the best military model (see Figure 7). The commercial operator is much more effective in preventing these types of unscheduled returns. The reasons for this are explained on page 112.

The commercial engine-caused return rates are also much lower, $82/10^6$ hours versus $274/10^6$ hours for the best military model. This is probably due to the commercial operators mission profile, maintenance program, and operator techniques.

Convenience and unncessary (diagnostics) returns are also much lower and reflect the economic concern of the commercial operator. The TBO achieved return rate is better than all but the military T53-L-11B engine ($139/10^6$ hours versus $144/10^6$ hours). However, the commerical TBO's are considerably higher than the military (see Figure 8).

In general, the commercial engines' return rates are lower than their military counterpart in every category, even when the military engines are flown in a peacetime environment.

MEAN-TIME-BETWEEN-DEPOT-RETURNS (MTBD): T53/T55 ENGINES

Figure 9 shows the advancement in mean-time-between-depot-returns (MTBD)* of engine causes for the T53 turboshaft engines over the years. First-generation engines, T53-L-1 through T53-L-11, show an increase from an MTBD for the T53-L-1/1A of 965 hours to 3, 300 hours for the T53-L-11C/11D. Second-generation T53-L-13-type engines show a similar increase, with the T53-L-13/13A MTBD at 1, 550 hours and the present T53-L-13B MTBD at over 4, 000 hours.

*Total model flying hours divided by the number of engine or component caused depot return events.

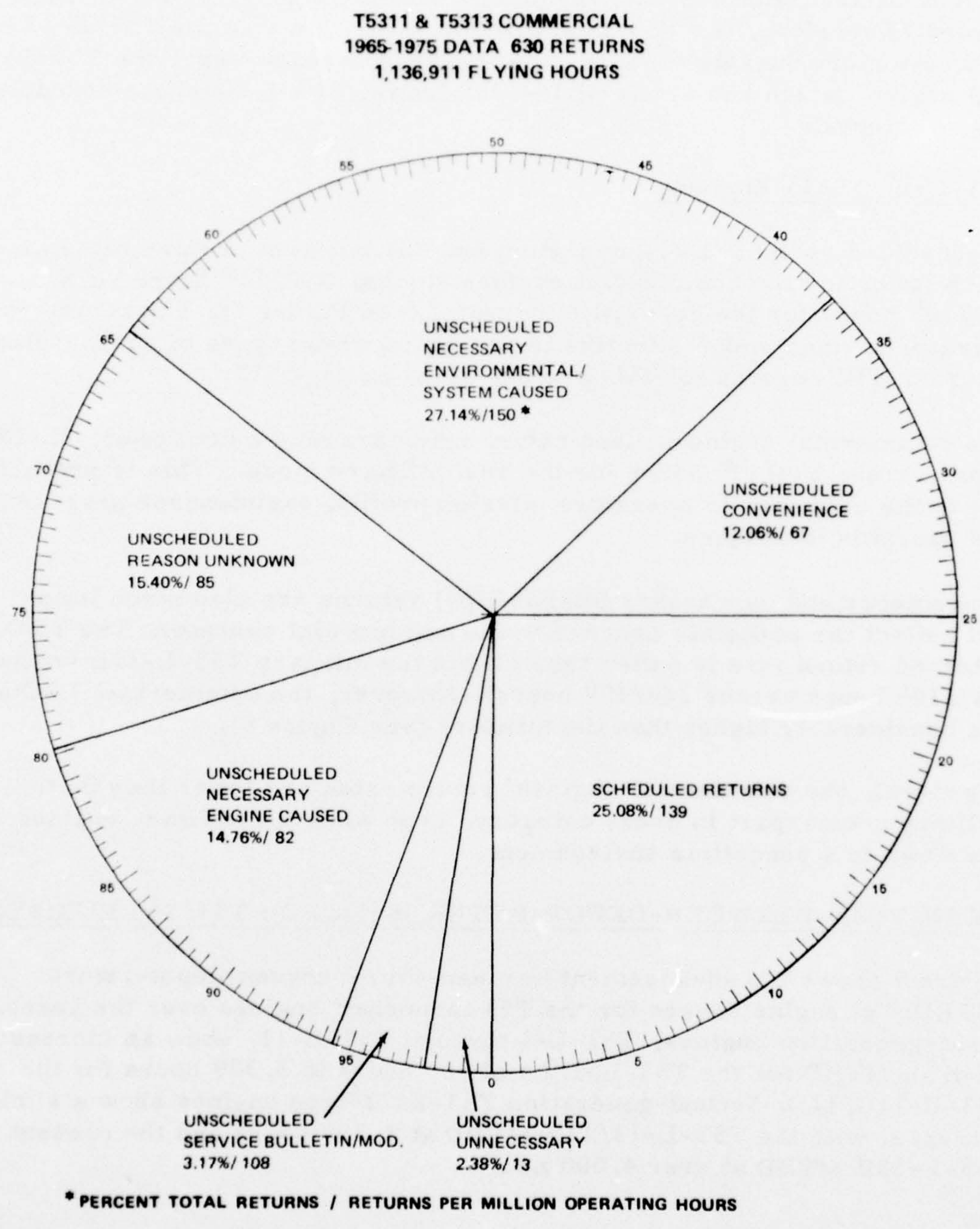


Figure 7. Summary of Depot Returns, T5311 and T5313 Commercial Engines

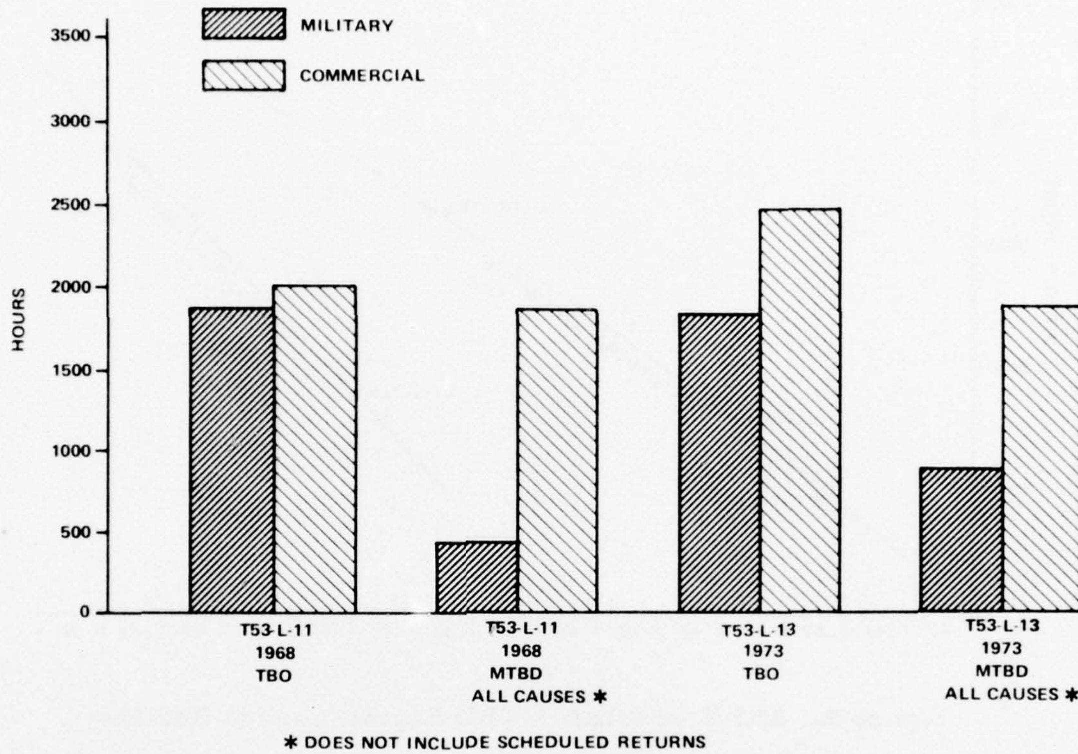


Figure 8. Depot Returns Comparison, Military Versus Commercial

SCHEDULED ENGINE RETURNS

The scheduled engine returns (composite engine) account for 6.48 percent of the total engine returns or 107 per million flying hours. While these figures differ somewhat between engine model and application, the military group remains below 10 percent. In contrast, over 20 percent of the commercial engines reach TBO. Figure 10 shows the difference in scheduled TBO growth rate for the T53 and T55 engines.

There is a tendency to compare the quality of an engine on the basis of numbers or percentages successfully reaching the TBO interval. However, if many of those engines fail to make TBO because of factors other than engine causes such as the environment, maintenance errors, or improper diagnosis of defects in the field, then the true potential of an engine is not realized. Similarly, if fewer engines are returned prematurely due to environmental causes, more are available to fail as a result of engine causes.

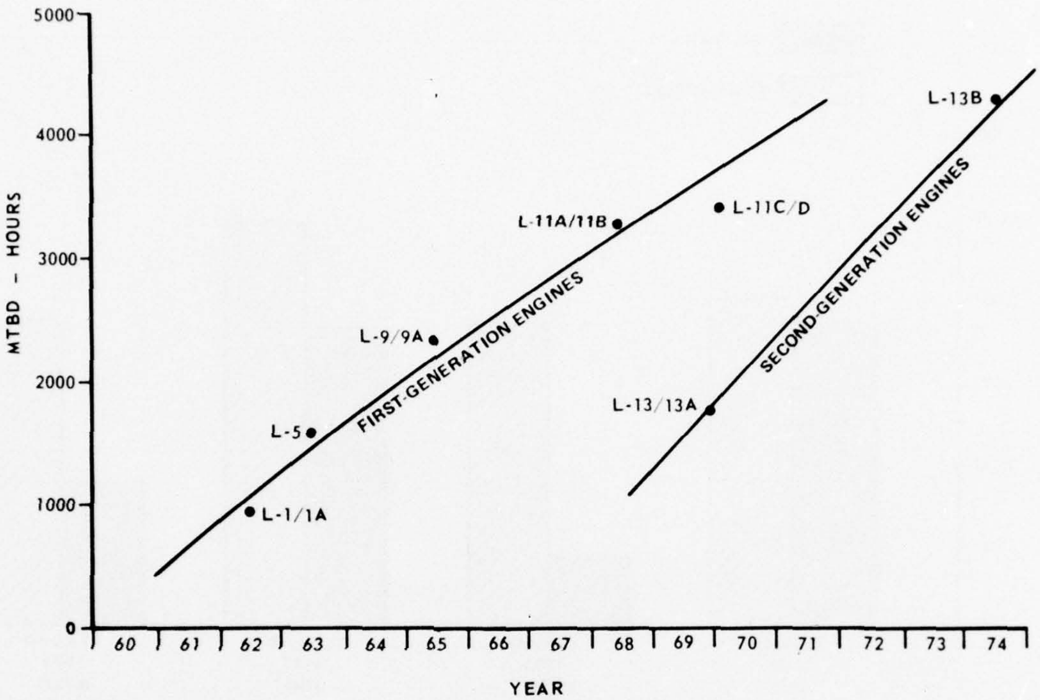


Figure 9. T53 Turboshaft MTBD Engine-Caused Returns

The reasons why so few engines reach their TBO goals, how the TBO interval is established, and how it can be increased are discussed in subsequent paragraphs.

UNSCHEDULED NECESSARY ENVIRONMENT-CAUSED RETURNS

Table 1 provides a comparison of each engine and the return rates for the various categories in this group.

Foreign Object Damage

Foreign object damage (FOD) is the most common cause of premature engine returns to depot. In the composite engine, FOD accounts for over 50 percent of those engines returned for operational environment causes (See Figure 11).

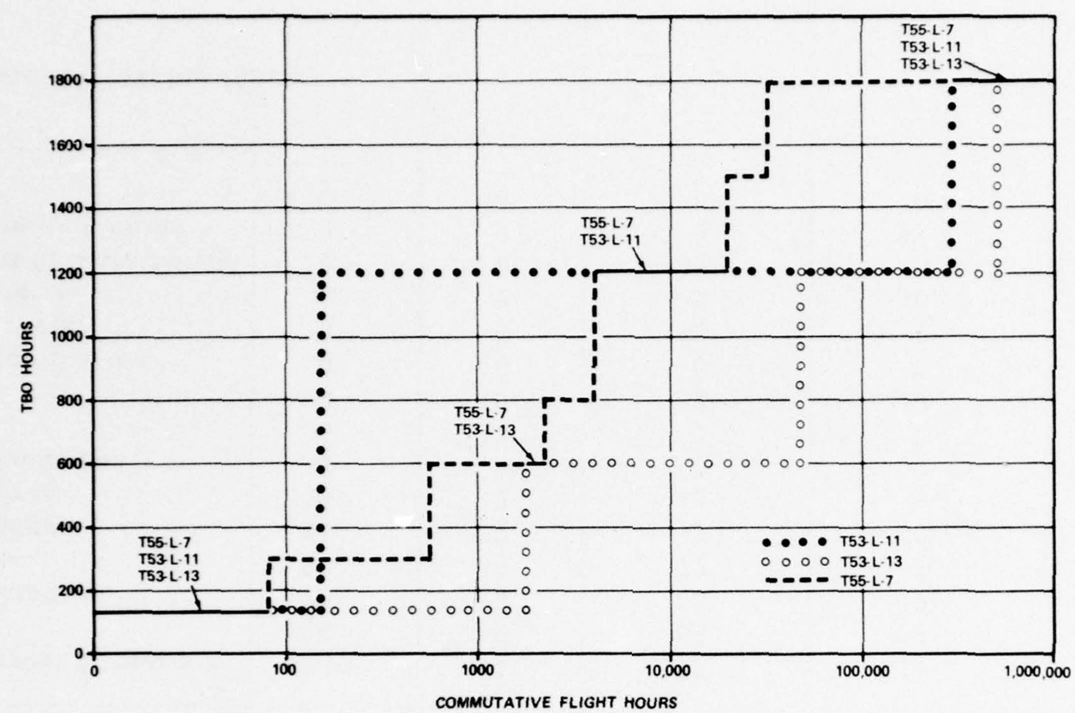


Figure 10. TBO Growth for T53-L-11, T53-L-13, and T55-L-7

Table 1. Unscheduled Necessary Environment-Caused Returns - All Engines

Return Categories	T53-L-11A/11B	T55-L-7B/C	T53-L-13A (Military)	T53-L-13B	T5311 and T5313 (Commercial)
Foreign Object Damage	672*	351	398	223	34
Erosion	404	199	66	8	44
Aircraft Accident	78	23	82	10	54
Maintenance	58	39	77	7	0
Battle Damage	41	20	39	9	N/A
Operator Error	10	9	18	8	2
Maintenance Error	8	0	0	0	10
Handling	5	12	0	0	0
Corrosion	0	10	2	14	0
Metal Contamination	0	6	0	0	0
Aircraft Caused	0	0	2	0	4
Cause Unknown	0	0	43	66	0
Power Shaft (Flame Spray)	0	0	34	0	0
Engine Damage (Other)	0	0	0	45	0
Overspeed	0	0	0	0	2

*Return Rate/10^6 Flying Hours.

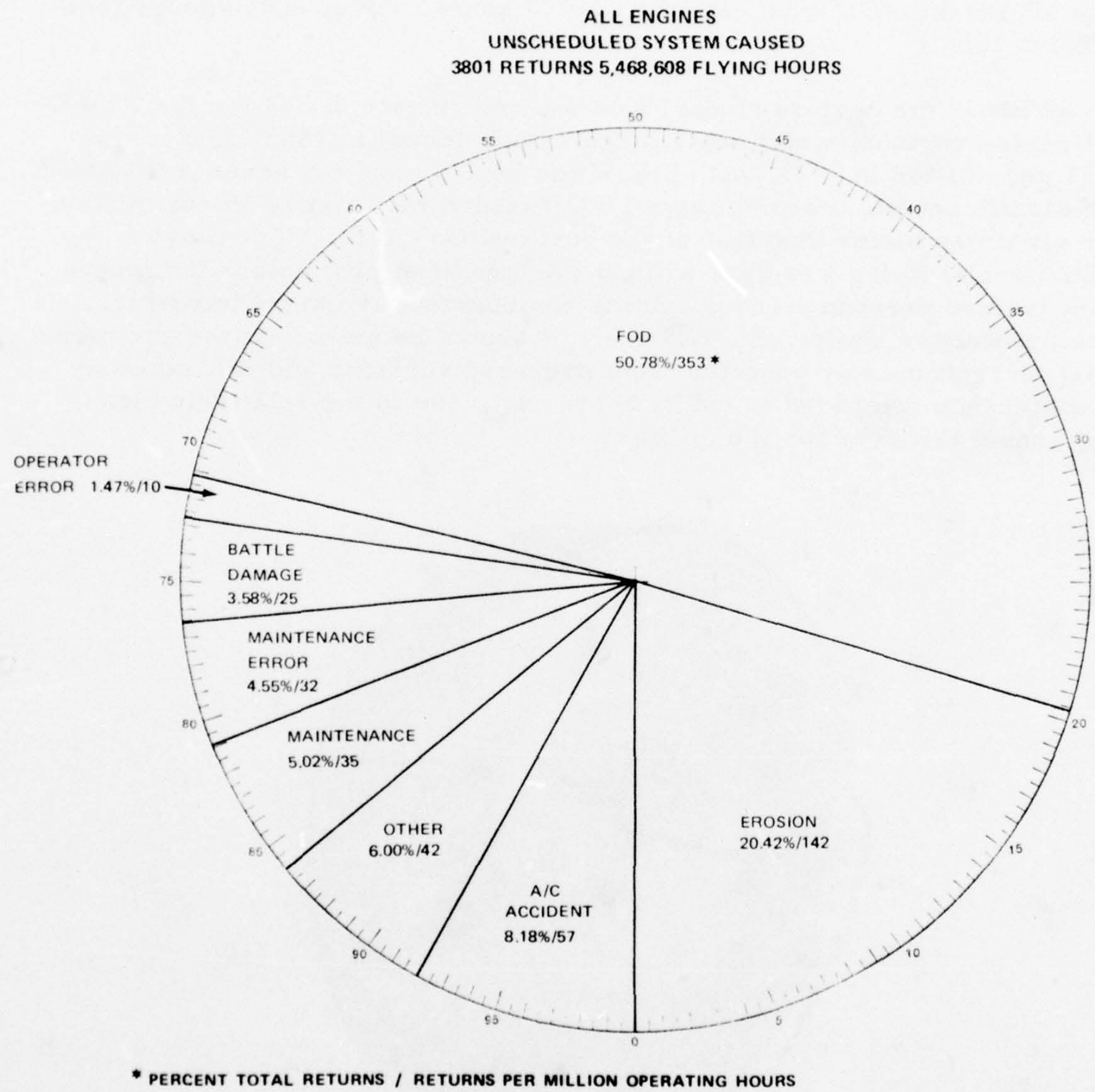


Figure 11. Composite Engine, Environment-Caused Returns

The earlier T53 series had neither FOD screens nor a particle separator, when originally designed and installed. But, as a result of the large number of returns, an effort began in the mid-1960's to equip these engines with "bolted-on" protection. These screens were successful and increased the MTBD for FOD from less than 1,000 hours to over 8,000 hours (see Figure 12).

A review of the engines studied shows a return rate of 672 for the T53-L-11 series engines, which were largely unprotected in 1968, to a low of 223 per million in 1973, with peacetime deployment and screens installed. Of significance is the commercial FOD return rate that is 35 per million or six times better than that of the best military rate. Since most of the commercial flying was done without the benefit of protection, it appears that trained personnel and operating environment are more important than protective equipment. However, it should be noted that the commercial aircraft usually operated from prepared surfaces and had excellent maintenance compared to military aircraft, due to the relatively high personnel turnover for the military.

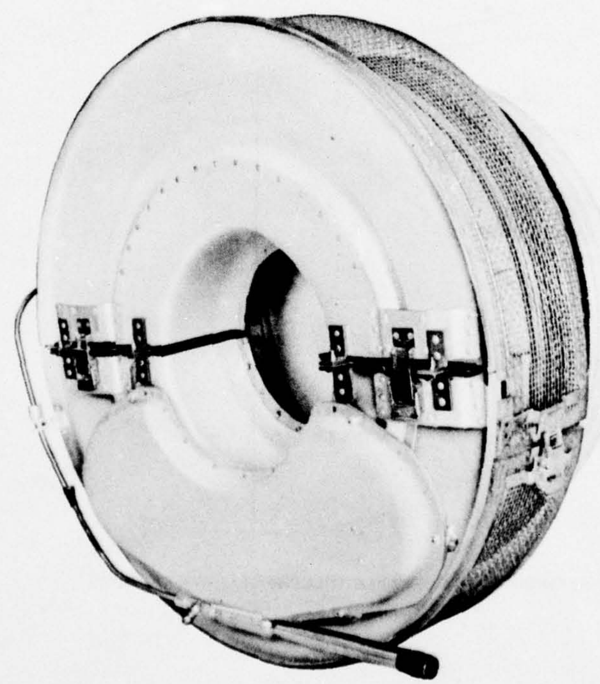


Figure 12. FOD Screen and Particle Separator

The current screen design appears to be adequate in preventing FOD frequently caused by gravel-size stones, rags, nuts, bolts, washers, cowling fasteners or ordnance. Smaller stones, rivets, hardware less than about 10/32 thread size and in particular small pieces of safety wire will go through present screens; although these items do not usually induce an engine-caused mission and safety abort, they often result in the premature return of an engine to depot.

Figure 13 shows the worldwide MTBD resulting from FOD for T53-L-11 and T53-L-13 type engines.

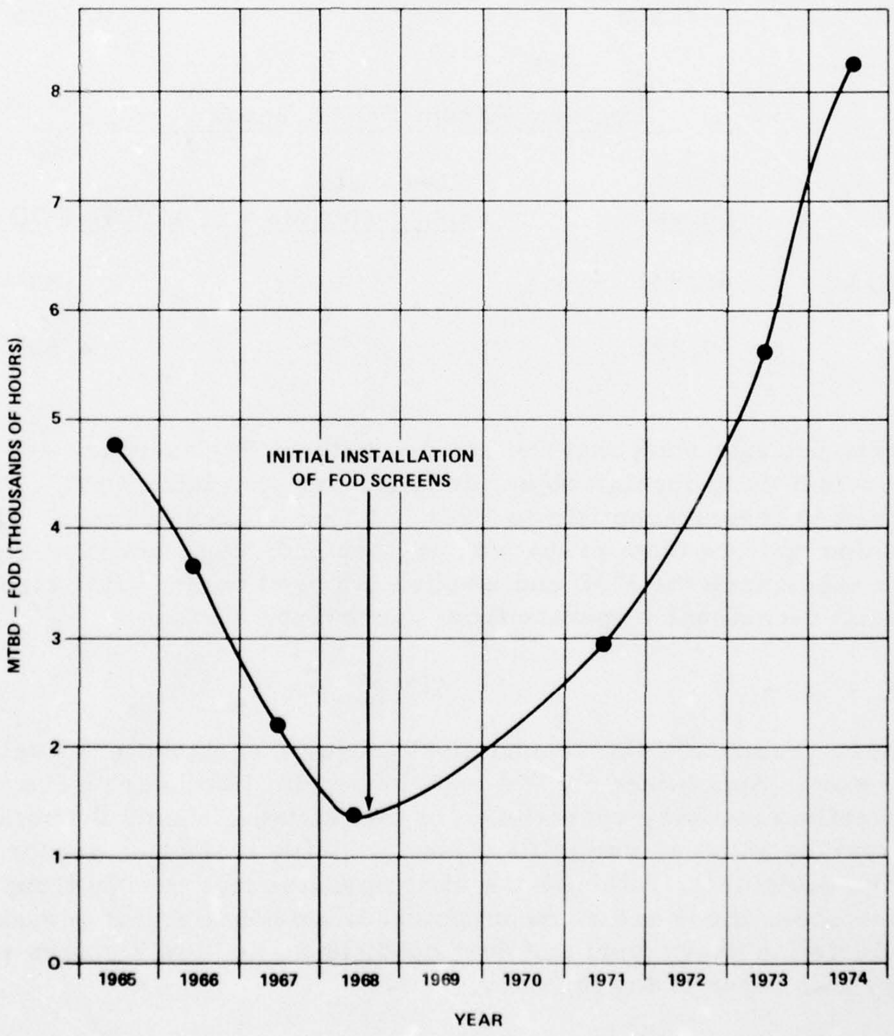


Figure 13. T53 Turboshaft Engines Worldwide MTBD Resulting From FOD

Also of interest was the effect of screen installation and aircraft utilization on the susceptibility of T53-L-13/13A/13B engines to foreign object damage. The results of the analysis of these variables are:

Engines With FOD Screens

	Flying hours	FOD-caused depot removals	MTBD-FOD (hour)
UH-1H/M	95,919	21	4,570
AH-1G	27,386	2	13,695

Engines Without FOD Screens

	Flying hours	FOD-caused depot removals	MTBD-FOD (hour)
UH-1H/M	66,841	80	836
AH-1G	9,392	2	4,695

These data not only show that the engines without FOD screens are far more susceptible to foreign object damage, but also indicate that the AH-1G aircraft is less susceptible to FOD, with or without screens. The AH-1G gunships operate from prepared surfaces and, consequently, are not likely to experience the FOD and erosion imposed on the UH-1 aircraft which must occasionally operate from unprepared surfaces.

Erosion

Compressor erosion is the second most frequent environmental cause for engine return. Approximately 404 engines per million hours were returned during wartime military operations. In comparison, the civil operator has been returning about 43 per million hours. Neither of these groups used protective equipment. Although the civil operator flys mostly from prepared surfaces, there are some instances when commercial operations are conducted in heavy sand and dust conditions, and their return rates then approach those of the military.

Compressor erosion of T53 engines became a serious problem upon heavy deployment of aircraft to Vietnam in 1965. Environmental conditions in Southeast Asia accelerated erosion of the compressor as a result of the heavy sand and dust encountered in the areas of operation. During 1966, the mean-time-between depot-returns (MTBD) resulting from erosion had dropped to a low of 2, 600 hours. Over 30 percent of the T53-L-11A/11B engine returns to depot were attributed to compressor erosion.

A sand and dust particle separator was developed during 1966 and shipment of the separator to the field began early in 1967. The sand and dust separator (Figure 14) mounted on the engine inlet is an inertial-type particle separator made in two halves. Engine inlet air enters the separator through a curved annular, radial inflow opening. Particles entering with the air are pulled out of the airstream and routed along a curved inner wall. A lip extending into the airstream deflects the particle-laden air into a large chamber, where the air velocity decreases. The larger particles settle in the chamber, while the finer particles are removed as the air is drawn through a fine mesh screen on the filter assembly. Removed particles are held in box assemblies containing porous plastic-foam inserts. The box assemblies had to be periodically removed and cleaned. A self-purging separator was introduced into the field during 1969; it is the same as described above except that the collector boxes were removed and an ejector nozzle was mounted on the plenum chamber at the 6-o'clock position.

With the introduction of the separators into the field and the buildup of installed engines using them, the MTBD due to erosion increased to 6,000 hours during the first two years and then climbed sharply to 15,000 hours by 1970. It now runs in excess of 100,000 hours. Figure 15 shows this improvement in MTBD erosion.

Maintenance Errors

Faulty maintenance practices are responsible for a significant number of engine returns to depot. Here again, the military returns are considerably higher than those of the civil operators. Two of the major problems experienced by the military in this area involved the use of flame-spray repair at overhaul.

During the Vietnam War, the unprecedented demand on the supply system caused shortages of some long lead-time items. One such item, a cast magnesium centrifugal compressor housing used in the T53 series engines, was seriously affected by erosion. Because of the short supply, a flame-spray repair procedure was developed in an effort to return some of the eroded housings to service (see Figure 16).

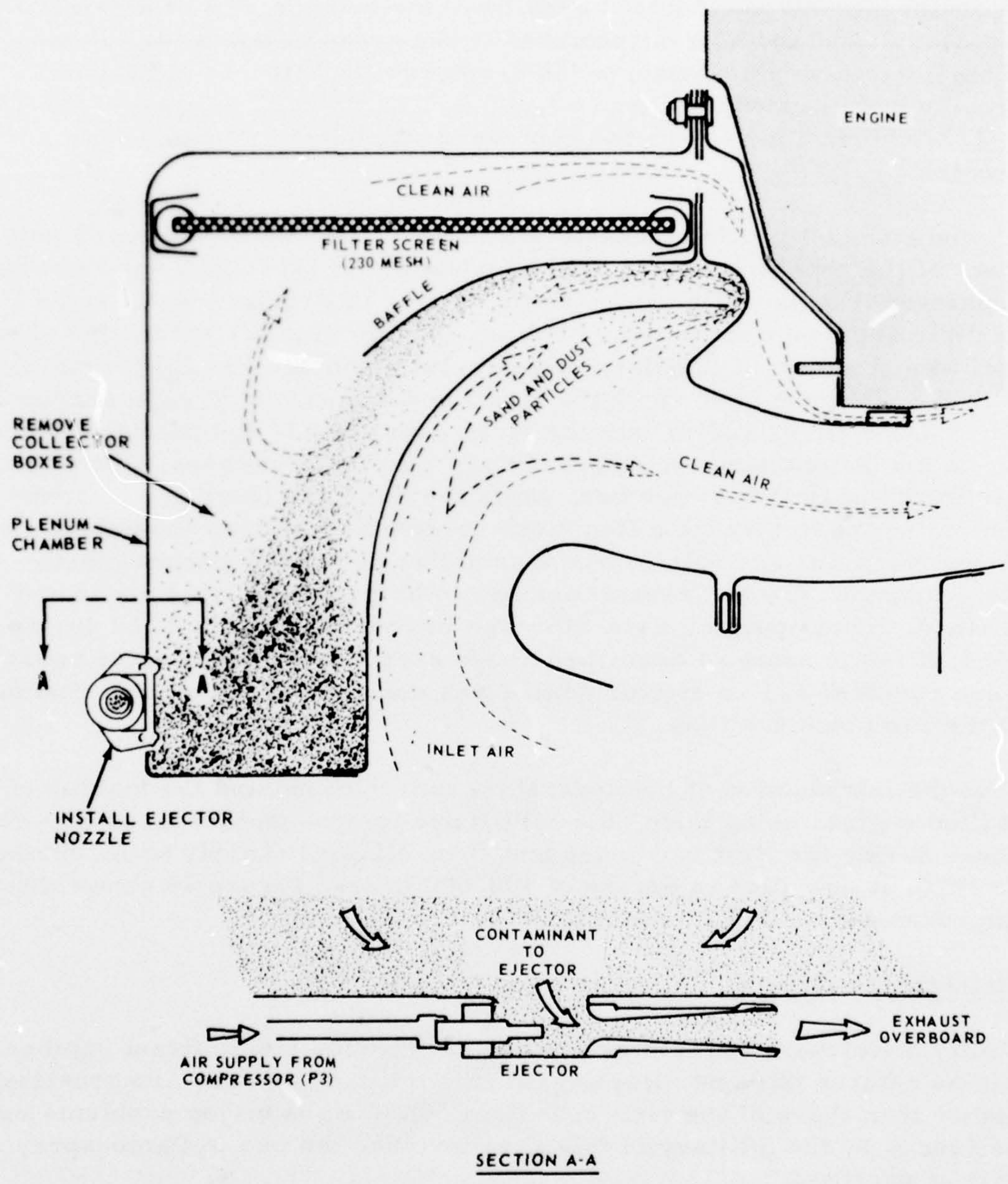


Figure 14. Modified First-Generation Sand and Dust Separator Incorporating Self-Cleaning Feature (Ejector Nozzle)

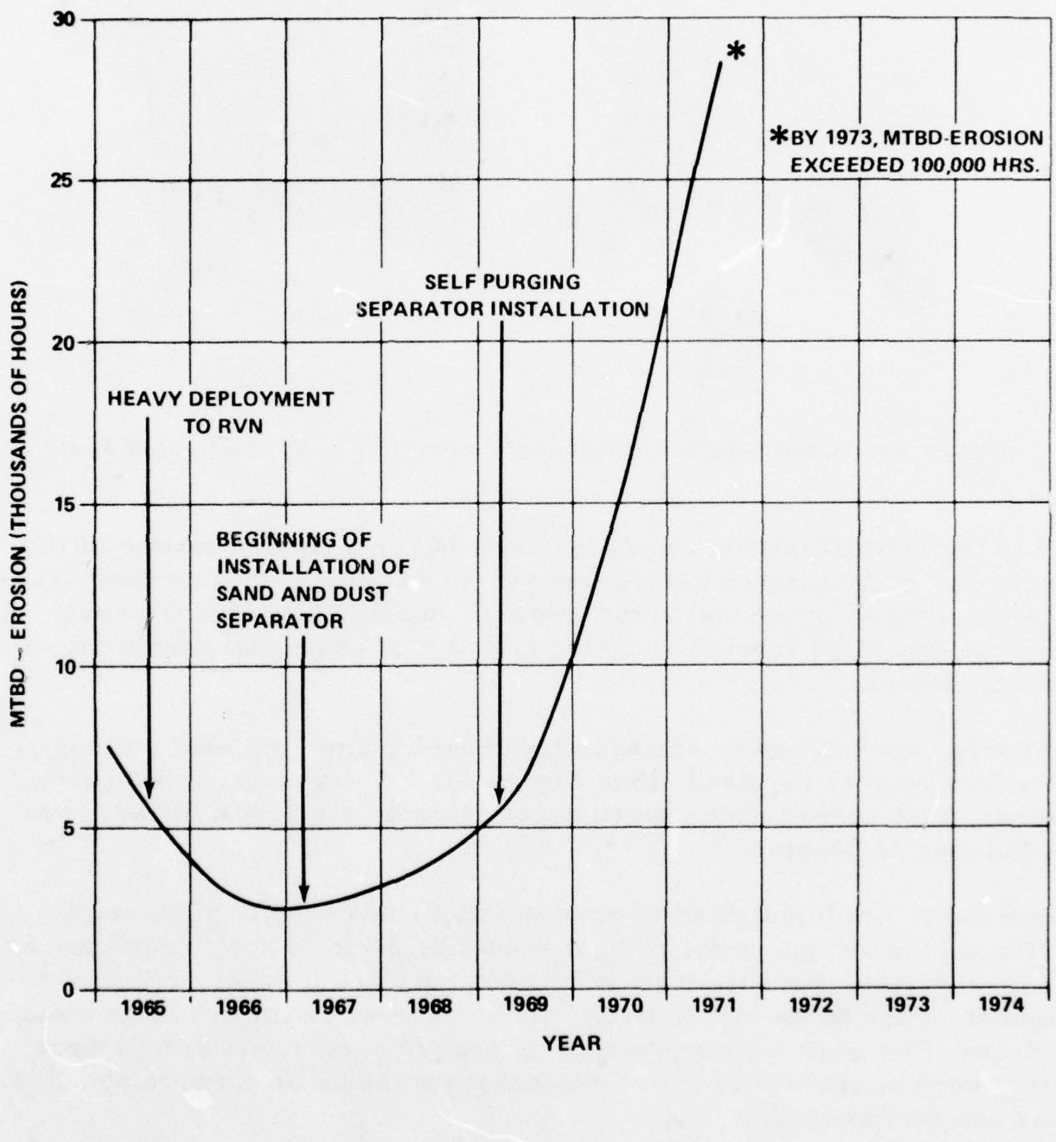


Figure 15. T53 Turboshaft Engines MTBD - Erosion

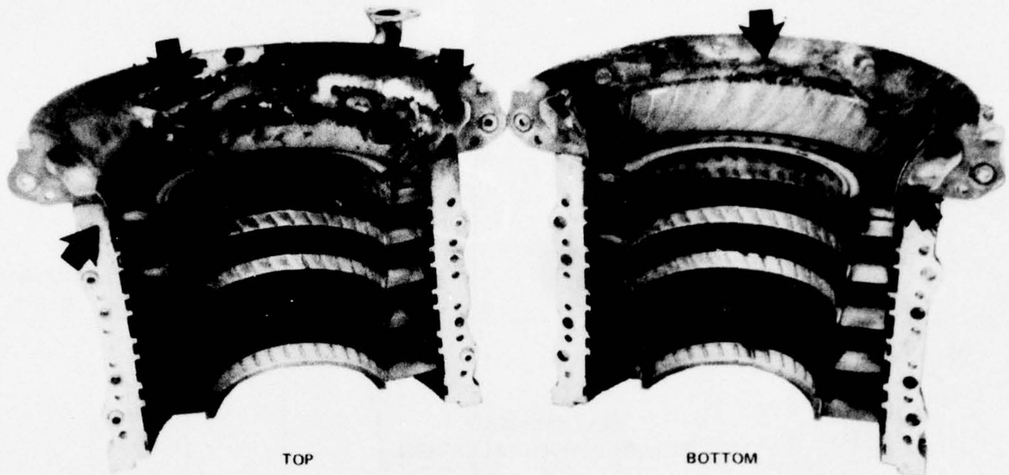


Figure 16. Centrifugal Compressor Housing Flame-Spray Repair

Due to the critical military need for engines, only limited testing of the repair was accomplished before this repair was introduced and repaired housings went into service; unfortunately, on some housings the spray material separated from the housing and caused additional unscheduled returns to depot.

Similarly, the T53 power shaft forward bearing area and seal journal were flame-spray repaired. (See Figure 17). This repair, in some instances, also caused unscheduled depot returns as a result of failure of the Number 21 bearing.

These cases are highlighted to point out that when selecting materials during engine design, some thought should be given to how normal wear can be repaired. Because it is difficult to bond any metallic material to magnesium due to its high activity, its use should be limited to nonwearing surfaces. The shaft bearing journal or seal running surfaces will wear during normal operation; thus, consideration should be given to how this wear can be repaired.

The review of engine returns due to maintenance errors also showed that some engines had been returned because improper shimming of the power shaft caused a rub with the compressor shaft.

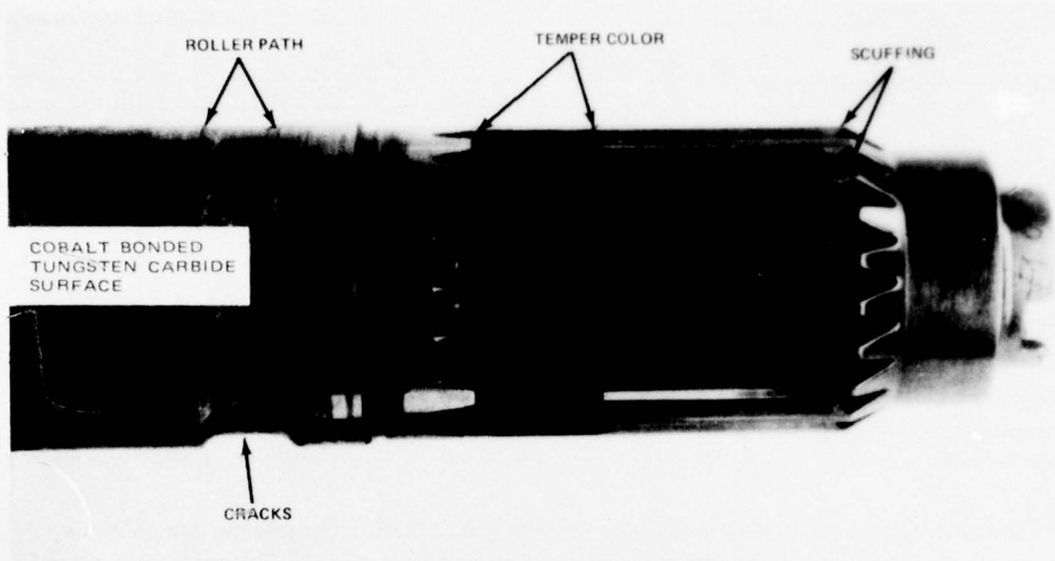


Figure 17. Power Shaft Flame-Spray Repair

It is concluded that all field replaceable components should be capable of being replaced without the need to perform any calculations, including the determination of proper shim size, bearing pinch, seal preload, turbine axial clearances, or gear backlash.

Additional Environment-Caused Returns

Engine returns for operator error, airframe causes, aircraft accident, and handling, can be related to human factors, training, and aircraft design. The rates for these groups are summarized in Table 2.

It appears that operator error is about eight or nine per million for the military, versus less than two for the civil operator (with the unaccountable exception of the T53-L-13A).

The accident return rates for the T55-L-7B/C, installed in the twin-engine CH-47 aircraft, are lower than those for the T53 series engine which is primarily used in single-engine aircraft. The rates of both commercial and military accidents are approximately the same. Consequently, it appears that military deployment and operation does not significantly affect aircraft accident rates.

Table 2. Additional Environment-Caused Returns

Event Rates Per Million Hours					
Engine	Operator Error	Airfame Causes	Aircraft Accident	Handling	Battle Damage
T53-L-11	9.6	(24)*	76	4.8	40
T55-L-7C	7.8	0	23	11.	19
T53-L-13A	18	2.3 (21)	82	1.7	39
T53-L-13B	8	10. (8.)	10	0	9.2
Commercial	1.7	4.3	53	0	N/A
Composite	10.2	3.3	64	2.7	24.9

*Airframe causes, chiefly engine-to-transmission coupling problems, accounted for a significant number of depot returns. The parenthetical rates in the tabulation above (extracted from the T53 ten-year report Lycoming Report No. 1628.5.15 Contract Number DAAJ01-74-C-0171) are more representative in this case.

The battle damage rate is consistent between the T53-L-11 series and the T53-L-13A. The T55-L-7 series rate is about one-half that of the T53 rate, probably due to the mission of the CH-47 aircraft.

The T53-L-13B data base was CY 1973, a peacetime year and, consequently, the battle damage return rate is much lower. These few returns were due to engines still in the supply line from the Vietnam War.

The T55 model engines used in the CH-47 twin-engine aircraft were analyzed to determine the effect of engine positions on component failure rates. The number 2 position engine was responsible for 32 percent more depot returns (all causes) then the Number 1 position.

Failure rates for selected components are listed below. It should be noted that the consistant differences are probably heavily influenced by different vibration environments for each position, due to mounting problems or other installation considerations.

Component	Position 1*	Position 2*
Fuel Control	199	473
Seals	83	141
Air Diffuser	75	166
Fuel Manifold	8	33
Connector, Main Manifold	0	41
Accessory Gearbox	48	75
Exhaust Thermocouple	0	25

*Failures per million operating hours.

UNSCHEDULED NECESSARY ENGINE COMPONENT-CAUSED RETURNS

The engine component-caused returns that were unscheduled but necessary are shown in Figure 18. Mainshaft oil seal failures proved to be the most frequent cause of premature depot returns, 37.62 percent. While not a safety-of-flight failure mode, seal leakage, or excessive oil consumption does nevertheless, require considerable maintenance effort. All of the seals studied during this investigation are of the positive-contact carbon-type.

Bearing failures account for almost all of the engine returns due to oil contamination and about 25 percent of the engine-caused returns. These roller and ball bearings have several failure modes, some of which have an impact on safety-of-flight.

Compressor rotor problems constitute the third largest category, largely due to T53-L-13A data. Included in this group in order of frequency are:

a. Compressor disc tenon cracks.

b. Centrifugal vane fracture.

c. Impeller mounting bolt fracture.

Cracks in the air diffuser, mostly at fittings and around vanes and tubes, caused approximately 5.25 percent of the engine returns, largely on T55 engines. Eventually, this part became field replaceable. However, this repair is difficult and time-consuming. Air diffuser cracks are not considered a safety-of-flight failure mode.

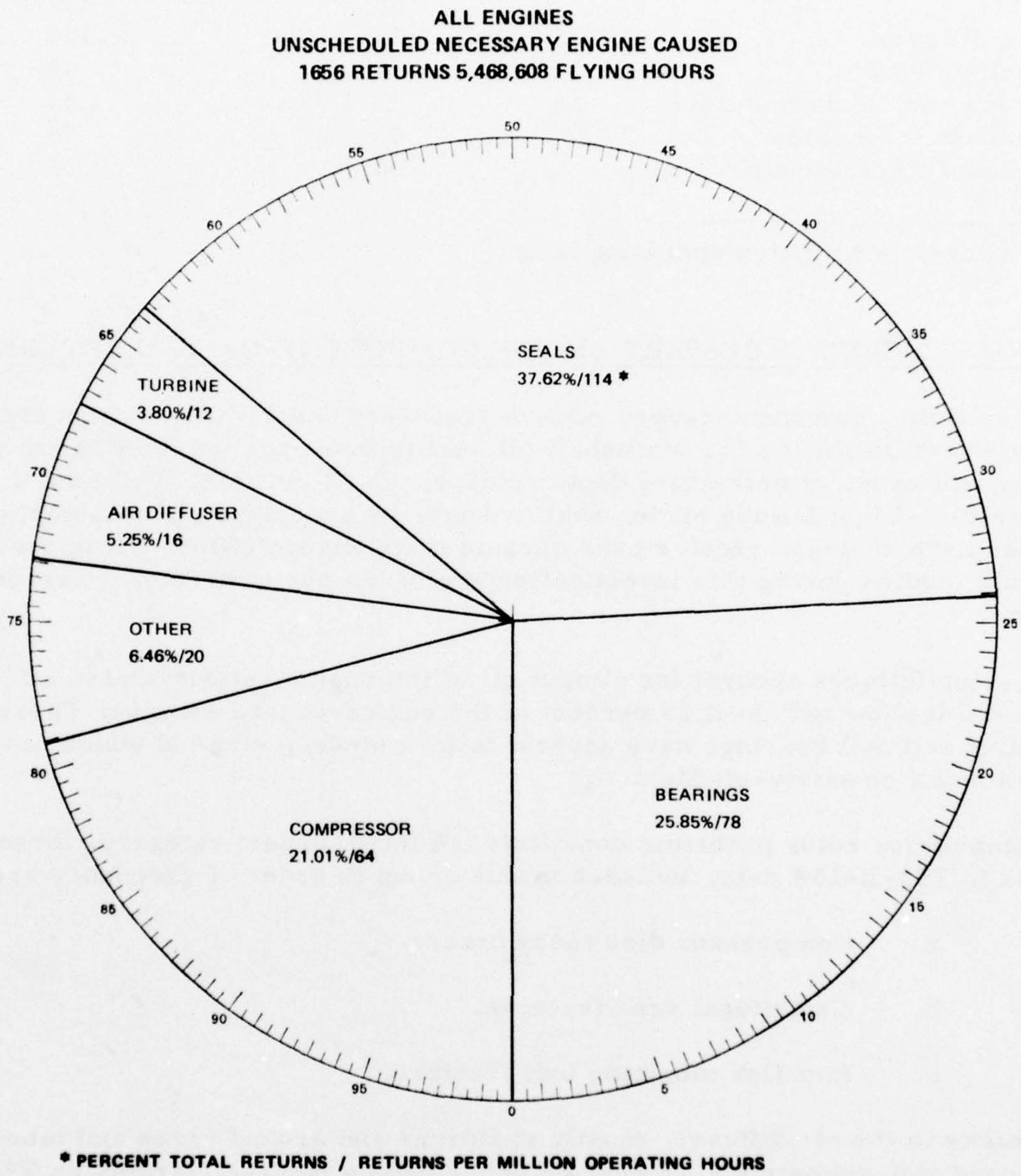


Figure 18. Composite Engine - Engine-Caused Returns

Turbine blades, blade retention, and turbine disc problems constitute the next category. While these problems have a low frequency of occurrence (only 12 per million hours), they result in total loss of power, with little or no warning.

The "other" category, shown in Figure 18, represent a group of engine returns (approximately 6 percent or about 20 per million operating hours) that are returned for various engine problems; but either the reason could not be confirmed or the records were incomplete, and they could not be properly classified.

Table 3 lists the components responsible for the composite engine-caused returns, ranked by order of occurrence; it also shows failure modes and their frequency of occurrence.

Table 4 compares engine component-caused returns to the different engine models and application in the sample data.

Returns Caused by Mainshaft Seal Failures

Oil leaks and excessive consumption, due to oil seal failures, are the largest contributor to engine-caused depot returns. While not a safety-of-flight failure mode, seal failures impose a considerable burden on maintenance activities. Even when seals are field replaceable, it is usually a difficult, time-consuming job that requires removal of the engine from the aircraft, special tools, and maintenance skills.

The seals described are carbon, positive-contact type and are installed around mainshaft bearings to prevent lubricating oil leakage. Typically, these seals must perform in a severe environment, generally at surface speeds from 0 to 19,000 feet per minute, at temperatures from ambient to 800°F, and at differential pressures of 50 to 60 psi across the seal for both air and oil sealing.

Tables 5 through 8 provide a summary of MTBD for seals by engine model, position, and year. It should be noted that 59 percent (204 engines) of 346 engine-caused depot returns were because of mainshaft seals.[1]

A discussion of the failure modes, specific causes, and corrective action follows.

[1] V. Bates, T53 Reliability and Maintainability Quarterly Progress Report, Avco Lycoming, Report Number 1625.5.12, U.S. Army Aviation Systems Command, St. Louis, Missouri, December 1973.

Table 3. Composite Engine-Caused Returns

Rank	Component	Occurrences	Failure Modes	No. of Events	Frequency X 10^6
1st	Carbon Seals	592 Engine Returns	Leakage	592	(108.2)
			Frozen Elements		
			Broken/Cracked Elements		
			Element Wear		
2nd	Bearings	374 Engine Returns			(68.4)
			Race Rotation	118	21.6
			Cage Failure	68	12.4
			Roller End Wear	23	4.2
			Race Spalling	8	1.5
			Failure Unknown	157	28.7
3rd	Compressor	349 Engine Returns			(63.8)
			Disc Rupture	249	45.5
			Blade Fracture	39	7.1
			Impeller Vane	22	4.0
			Fatigue of Impeller Bolts	39	7.1
4th	Air Diffuser	75 Engine Returns	Cracks in Vanes, Tubes Tubes and Supports	75	13.7
5th	Turbines	50	Blade Fracture	48	8.8
			Blade Retaining Ring	2	0.4

Table 3. Composite Engine-Caused Returns (Continued)

Rank	Component	Occurrences	Failure Modes	No. of Events	Frequency X 10^6
6th	Power Turbine Oil Impeller	10	Silver Plate Flaking Caused Oil System Contamination	10	1.8
7th	Gears and Splines	7			(1.3)
			Tooth Wear Spalling	4	0.7
			Spline Wear	2	0.4
			Chipped Tooth	1	0.2
8th	Stators	4	Lead Seal Broken	4	0.7
9th	Power Turbine	1	Crack in Vane Support	2	0.4
10th	Combustor Liner	1	Broken Attach Brackets	1	0.2

Table 4. Unscheduled Engine Component-Caused Depot Returns

Return Rate/10^6 Flying Hours

Return Categories	T53-L-11/11B	T55-L-7B/C	T53-L-13A (Military)	T53-L-13B	T5311 & T5313 (Commercial)
Seal Leakage	55	369	141	173	19
Number 4 Bearing	27	-	1	15	2
Number 2 Bearing	26	131	29	16	5
Number 1 Bearing	26	18	8	13	6
Number 3 Bearing	11	-	2	0	0
Number 21 Bearing	17	-	18	8	17
Air Diffuser	19	80	7	7	4
GP Turbine	26	0	5	0	1
Power Turbine	12	0	1	0	2
Number 6 and 7 Bearings	-	37	-	-	-
Torquemeter Bearing	-	37	-	-	-
Compressor	0	10	141	70	17
Number 4 and 5 Bearings	-	4	-	-	-
Number 30 Bearing	-	6	-	-	-
Number 26 Bearing	-	4	-	-	-
Centrifugal Impeller	0	0	3	0	0
Sun Gear Failure	0	-	2	0	1
Fuel Control	0	0	2	0	0
Number 10 Bearing	0	-	0	0	1
Number 9 Bearing	0	-	0	0	1
Other	54	12	15	0	4

Table 5. Number 1 Seal Failures

	MTBD				
	1967	1968	1969	1970	1971 (1st Half)
T53-L-11A/11B	(39) 38,600	(36) 41,800	(75) 14,600	(70) 13,100	(30) 10,850
T53-L-13/13A	(10) 28,500	(85) 12,815	(263) 7,365	(157) 15,145	(24) 21,100
T53-L-13B	N/A	N/A	N/A	(3) 21,890	(35) 13,790
T53-L-7/7A	(15) 7,565	(6) 27,835	(10) 17,295	(12) 11,250	(5) 10,750
T53-L-15	N/A	(0)	(9) 4,590	(22) 2,540	(9) 2,590

NOTE: Numbers in parenthesis are the total failures resulting in depot returns for each engine model for each calendar year.

Table 6. Number 2 Forward Seal Failures

	MTBD				
	1967	1968	1969	1970	1971 (1st Half)
T53-L-11A/11B/11C/11D	(8) 188,470	(13) 115,720	(23) 47,650	(12) 76,430	(5) 65,110
T53-L-13/13A	(21) 13,570	(176) 6,190	(328) 5,905	(488) 4,875	(60) 8,440
T53-L-13B	N/A	N/A	N/A	(0)	(2) 241,340
T53-L-7/7A	(2) 56,750	(1) 167,000	(1) 172,960	(7) 19,280	(0)
T53-L-15	N/A	(0)	(5) 8,260	(21) 2,660	(6) 3,890

NOTE: Numbers in parenthesis are the total failures resulting in depot returns for each engine model for each calendar year.

Table 7. Number 2 Aft Seal Failures

	MTBD				
	1967	1968	1969	1970	1971 (1st Half)
T53-L-11A/11B/11C/11D	(9) 167,530	(12) 125,360	(15) 73,060	(5) 183,400	(2) 162,770
T53-L-13/13A	(6) 47,500	(7) 155,600	(15) 129,125	(22) 108,100	(2) 253,165
T53-L-13B	N/A	N/A	N/A	(0)	(0)
T53-L-7/7A	(1) 113,500	(0)	(2) 86,480	(1) 134,965	(0)
T53-L-15	N/A	(0)	(1) 41,290	(1) 55,860	(0)

NOTE: Numbers in parenthesis are the total failures resulting in depot returns for each engine model for each calendar year.

Table 8. Number 3 Seal Failures

	MTBD				
	1967	1968	1969	1970	1971 (1st Half)
T53-L-11A/11B/11C/11D	(5) 301,550	(21) 71,635	(44) 24,910	(38) 24,130	(11) 29,600
T53-L-13/13A	(1) 285,000	(12) 90,760	(25) 77,475	(27) 88,070	(10) 50,635
T53-L-13B	N/A	N/A	N/A	(1) 65,675	(3) 160,900
T53-L-7/7A	(2) 56,750	(6) 27,835	(5) 34,560	(3) 45,000	(2) 26,870
T53-L-5	N/A	(0)	(0)	(1) 55,860	(0)

NOTE: Numbers in parenthesis are the total failures resulting in depot returns for each engine model for each calendar year.

The original Number 1, Number 2 (forward), and Number 2 (aft) seals in the T53 series engines were floating carbon rings with a small gap between the shaft runner and the carbon. These configurations were satisfactory for the early engine; however, as the engine was uprated and air pressures and temperatures increased, the gap in the seals allowed too much airflow and three element segmented circumferential seals were introduced. Figure 19 shows the T53-L-11 Number 2 package and its operating conditions. Figure 20 shows the Number 1 seal, which is the same as the T53-L-13 and T53-L-11 engines.

Problems occurring with the Number 1 seal were carbon wear and coking, which resulted in oil leakage. The carbon wear is a result of high interface pressure between the carbon and the runner at high speed and power. Pressurization air of 53 psia at engine maximum power presses the carbon segments onto the runner. Carbon wear then progresses to a point where the segments are no longer touching the runner. This condition, which produces a minimum gap at full load and speed, is acceptable. Coking and oil leakage are a result of two problems. If the pressurization air at idle drops to too low a value, oil will leak past the carbons, coke up the elements, and escape into the air stream. One fix that alleviated this problem was the incorporation of six blow holes in the seal housing that connects the center of the seal to the bearing cavity. Any oil that leaks past the oil side of the seal will be blown back into the bearing cavity through these holes. Another cause of the Number 1 seal coking and oil leakage was oil leakage of the forward Number 2 seal. The oil traveled through the intershaft area and was blown into the Number 1 seal with the pressurization air. The solution to this problem lies in the advanced Number 2 seal configurations.

The most recent improvement of the Number 1 seal was a change to a face seal configuration. Figure 21 illustrates the design. This improved face seal has been qualified and is incorporated in the latest T53 models. Advantages of the face seal are a positive-contact seal at shutdown, and the centrifugal force tends to pump oil back into the bearing cavity during operation.

The original Number 2 bearing package (Figure 22) in the T53-L-13 experienced a high-speed oil leakage problem because of a pressure differential across the package. This pressure differential of 10 psi across the bearing cavity caused oil to leak out of the forward seal. The problem was solved by connecting the forward air cavity to the center of the aft seal, creating a zero-pressure differential across the cavity. An oil leakage problem remained at low speeds due to insufficient air-to-oil pressure differential. This was eliminated by increasing the scavenge

OPERATING PRESSURES

	IDLE (12,500 RPM)	MAXIMUM (25,000 RPM)
EXTERNAL FWD	4.0 psig	37.0 psig
EXTERNAL AFT	1.5 psig	21.0 psig
AFT PRESSURIZATION	4.0 psig	36.0 psig
AIR TEMPERATURE	300°F	600°F

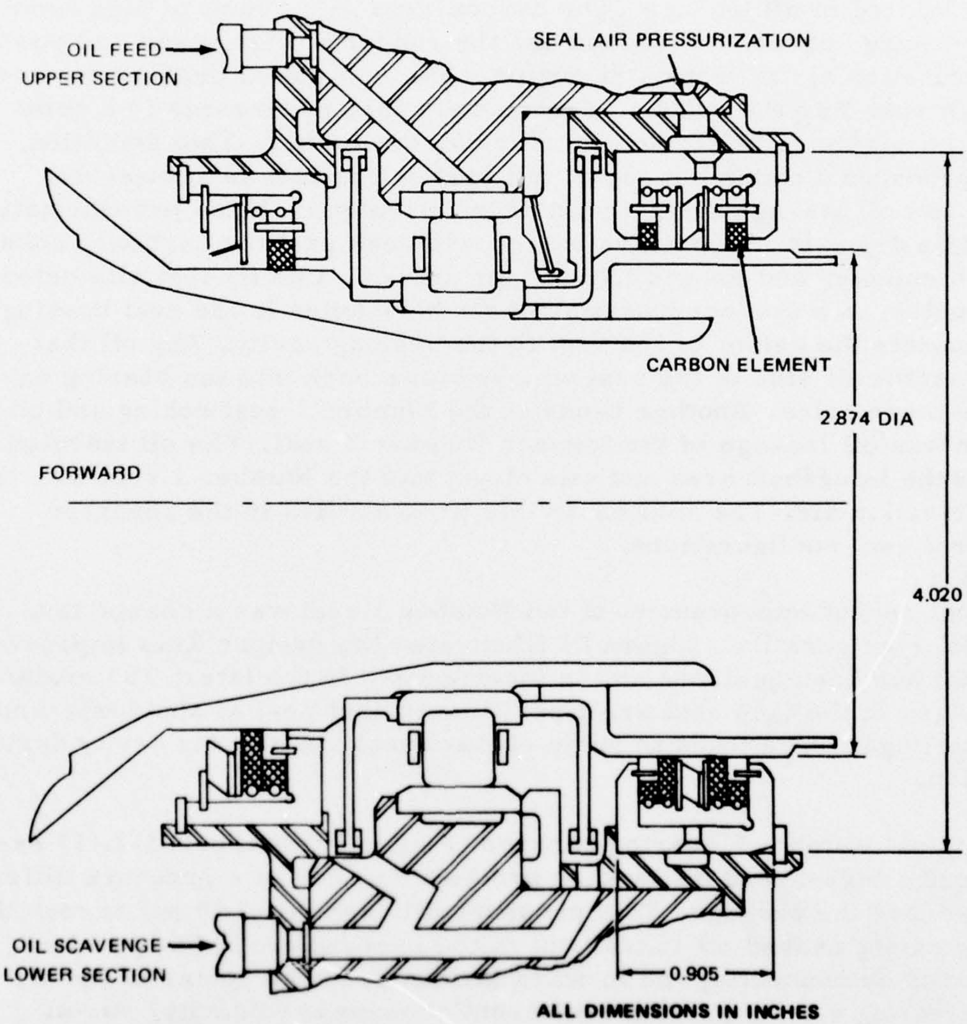


Figure 19. T53-L-11 Number 2 Bearing Package

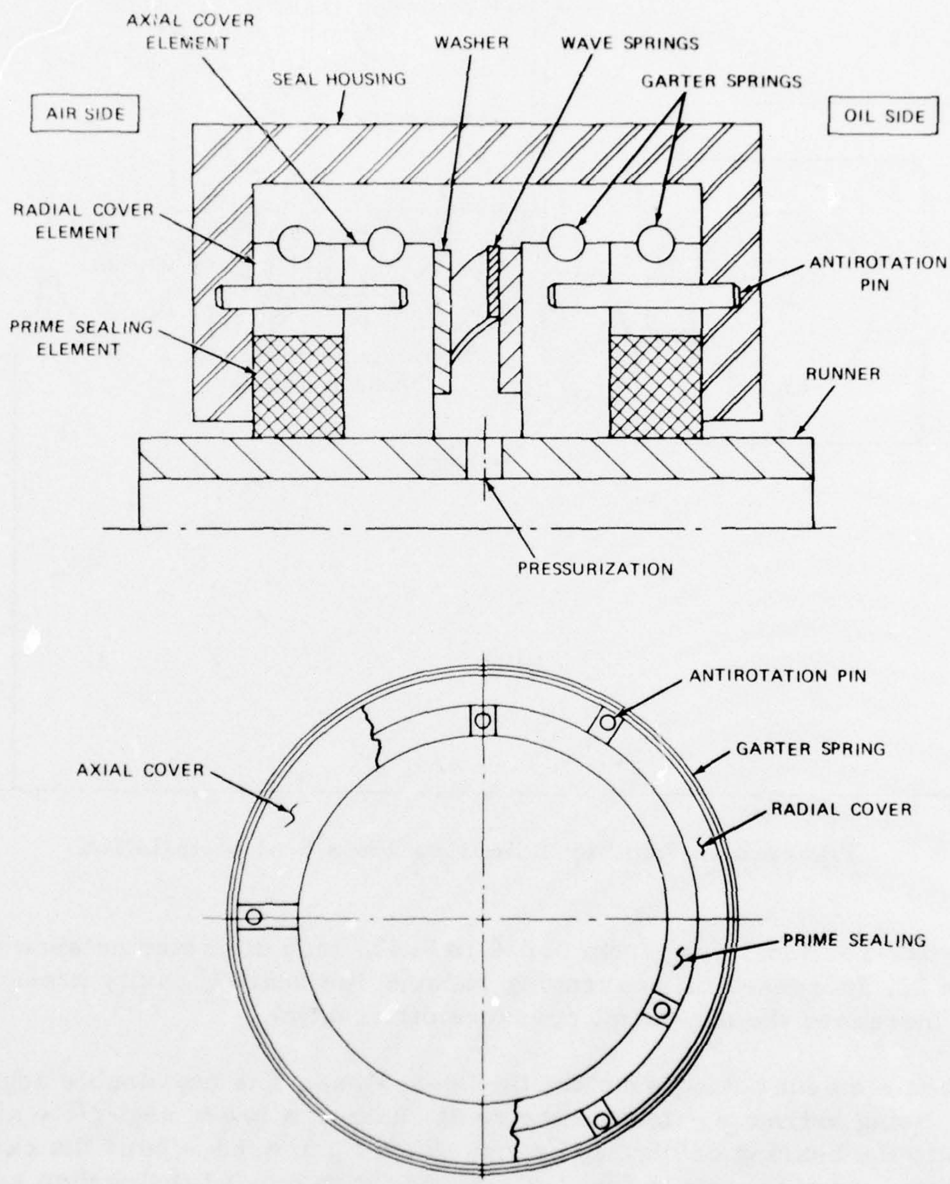


Figure 20. Number 1 Double-Row Segmented Positive-Contact Pressurized Seal

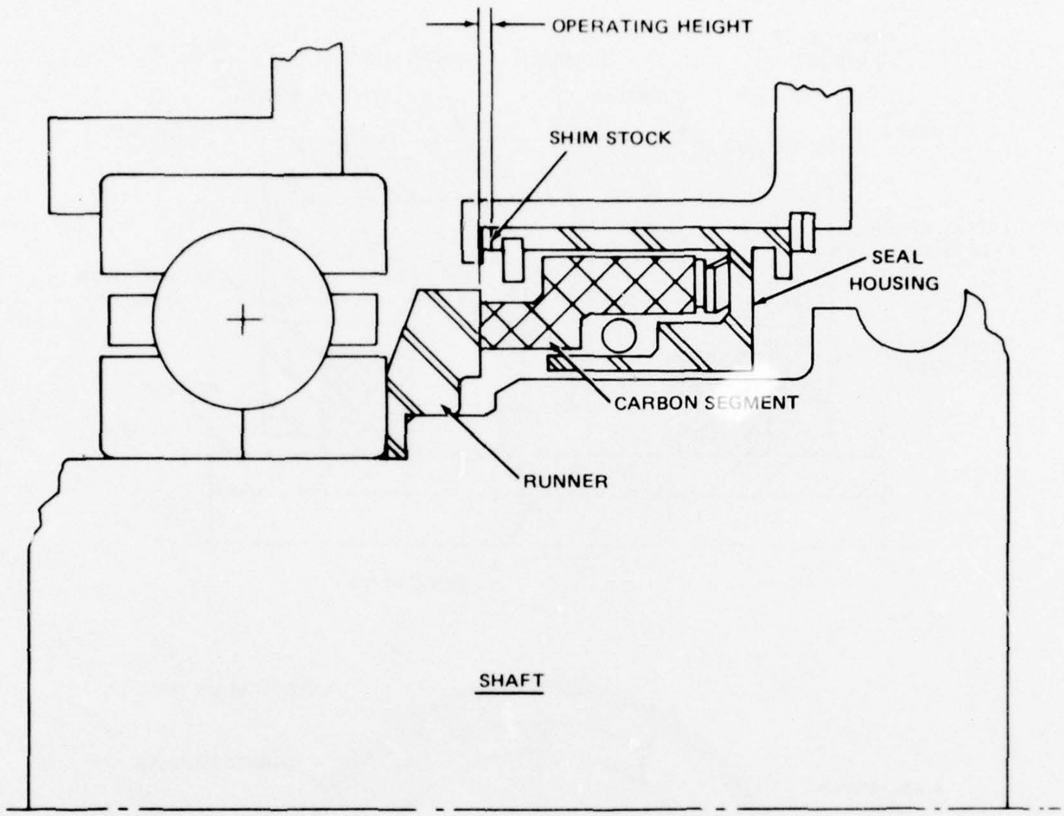


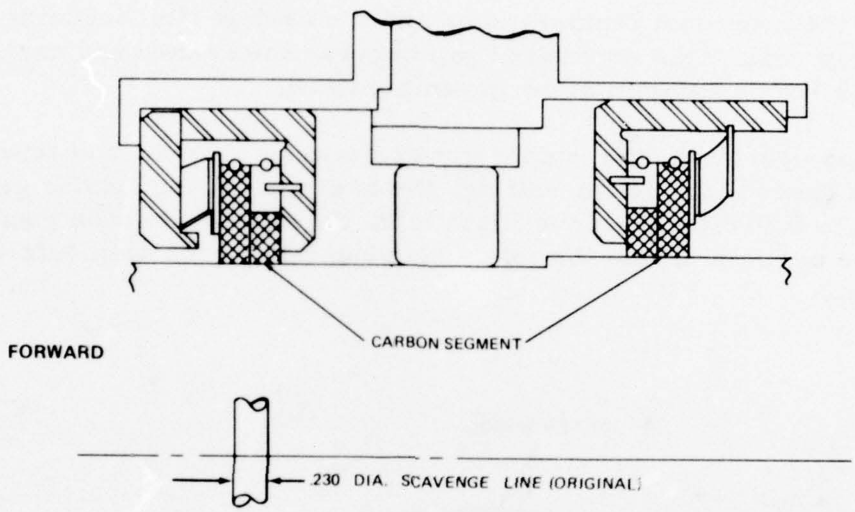
Figure 21. Number 1 Bearing Face Seal Installation

line cross-sectional area from 0.230 to 0.430 inch diameter as shown in Figure 22. Increased oil scavenging reduced the bearing cavity pressure, which increased the air-to-oil pressure differential.

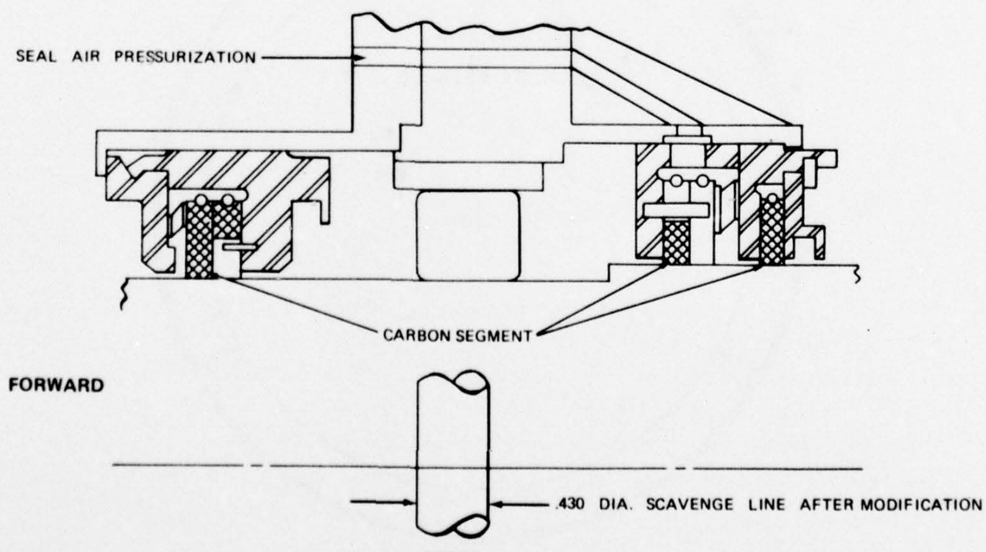
A carbon element coking problem then developed. The new double segment seals, being extremely tight on the shaft runner, allowed negligible airflow into the bearing cavity, and excessive oil gathered around the carbon segments, causing coke to form. Coke pads then caused the carbon segments to stick open and allow excessive airflow into the bearing cavity. This problem was solved by developing a single-segment element (3-piece sawcut) configuration (Figures 23 and 24), which permits a controlled airflow into the bearing cavity from the start to keep the seal element clean and free of coke deposits.

OPERATING CONDITIONS

	IDLE (13,000 RPM)	MAXIMUM (25,000 RPM)
EXTERNAL FWD.	7.0 psig	50.0 psig
EXTERNAL AFT.	4.0 psig	60.0 psig
AIR TEMPERATURES	350°F	800°F



BEFORE



AFTER

Figure 22. T53-L-13 Number 2 Bearing Package Schematic

The sawcut seal design (Figure 23) is a positive-contact, single carbon ring cut into three equal segments for sealing. Three sawcuts or joints are from 0.0009 to 0.012 inch wide when installed on the runner. The total orifice area was 0.0001 square inch.

When the bore of the carbon sealing segments wears in the sawcut seal design, the sawcuts close. As the bore of the segments wears, the sawcuts close completely at room temperature, and the carbon ring becomes a controlled gap seal. This controlled gap between the runner and carbon ring is 0.005 inch maximum at room temperature.

During engine operation, the runner grows because of speed and temperature. At the ground idle power setting, the average carbon runner gap would close to 0.002 inch. Above flight idle, the average carbon runner gap would be negligible, and the joints between the carbon elements would begin to open.

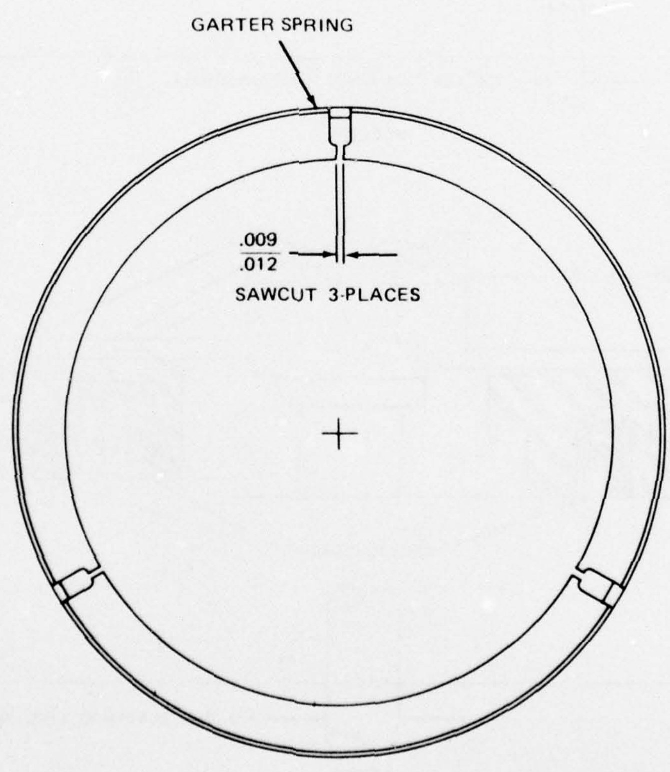


Figure 23. Number 2 Seal for Improved Scavenging Airflow Sawcut Seal Design

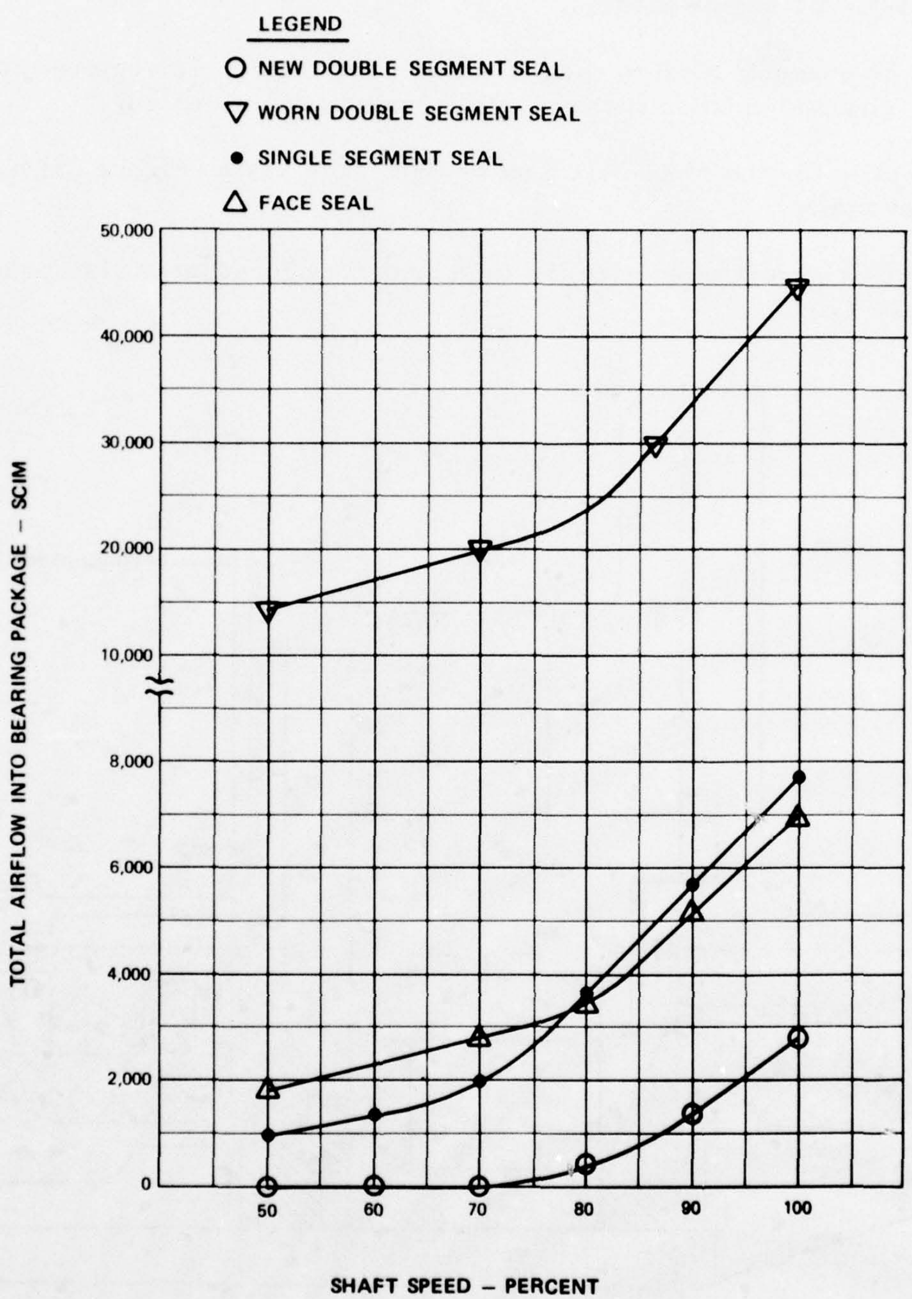


Figure 24. Typical Number 2 Bearing Package Airflow Versus Shaft Speed

This sawcut configuration is now operating successfully in the T53-L-13B and T53-L-701 engine models.

Figure 24 presents airflow measurements for the double segment configuration, new and used, and the single element sawcut design.

As a backup for the single element design, face seals (Figure 25) have been developed.

The airflow experienced with the face seal configuration is also presented in Figure 24.

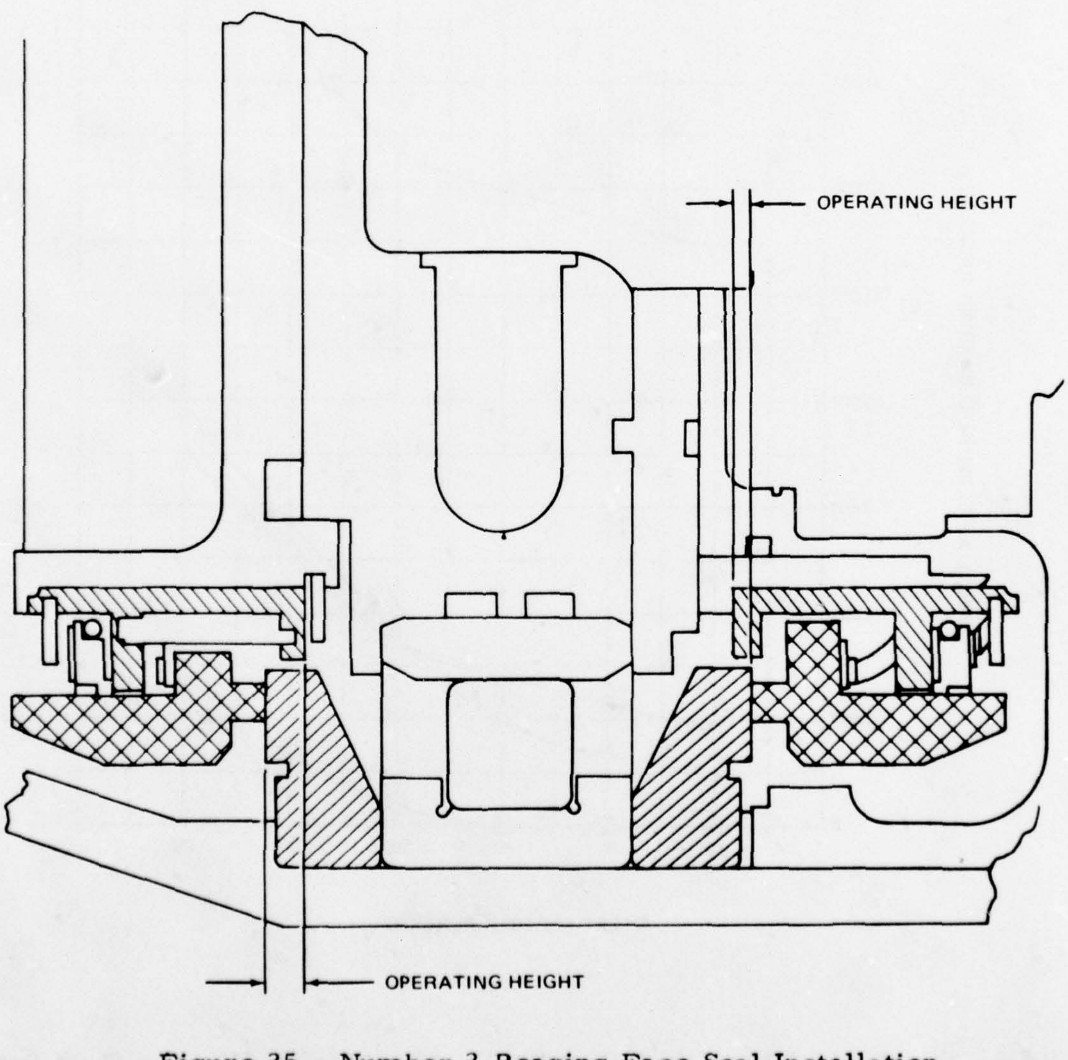


Figure 25. Number 2 Bearing Face Seal Installation

A Weibull plot (Figure 26) was made for the Number 2 forward seal from a sample of 300 engine returns, including 32 seal leakage events. A characteristic life of 1,748 hours was established, at which point 63 percent of the seals would have failed. The slope β was determined to be 2.16, indicating a positive correlation between time and failure rate. A Weibull plot (Figure 27) was also prepared for the Number 1 seal. Again, 300 engine returns were used with 20 seal failures occurring, which gives a characteristic life of 2,980 hours at which 63 percent of the seals would have failed. The slope of the regression line in this case was 1.60. Both the Number 1 and the Number 2 seals show increasing failure rates with respect to time; nevertheless, wearout was not the prime failure mechanism. Rather, buildup of coke deposits with respect to time was the most likely cause, accumulating to a point at which the segment froze and leakage occurred.

Returns Caused by Bearing Failures

As previously mentioned, for the engine-caused category, oil contamination is the second highest cause of engine returns for overhaul. Even when the offending parts are field replaceable, aviation units are reluctant to place an engine back into service unless they are absolutely sure that all contaminants have been removed from the lubrication system, pumps, lines, hoses, coolers, bearing cavities, and internal drilled passages.

This study revealed that for the selected engine sample, most of these returns were caused by bearings and, more specifically, that the most frequent failure mode was bearing outer race rotation, followed by cage and roller failures. Race rotation is not a safety or mission impacting event but often generates enough metal to trigger the Spectrometric Oil Analysis Program (SOAP) alert or to illuminate the chip detector, which may cause an aborted mission or a precautionary landing. A cage fracture is a safety and mission impacting event that usually results in total engine failure and a forced landing. Most cage failures gave insufficient warning for either SOAP or the chip detector to be effective (see Table 14, Page 103). This is discussed in more detail under the diagnostic section. Table 9 shows the bearing MTBF's for the T53 engines at selected positions for a period of several years. Of these, the Number 21 bearing caused the most didficulties, due in part to misalignment between the shaft and bearing. A Weibull plot (Figure 28) shows a B slope of .49 or a failure rate decreasing with time. This is to be expected since misalignment leads to an early failure, and if initial alignment is satisfactory, the bearing will last its normal life. Historical development of these bearings and their modifications are summarized as follows:

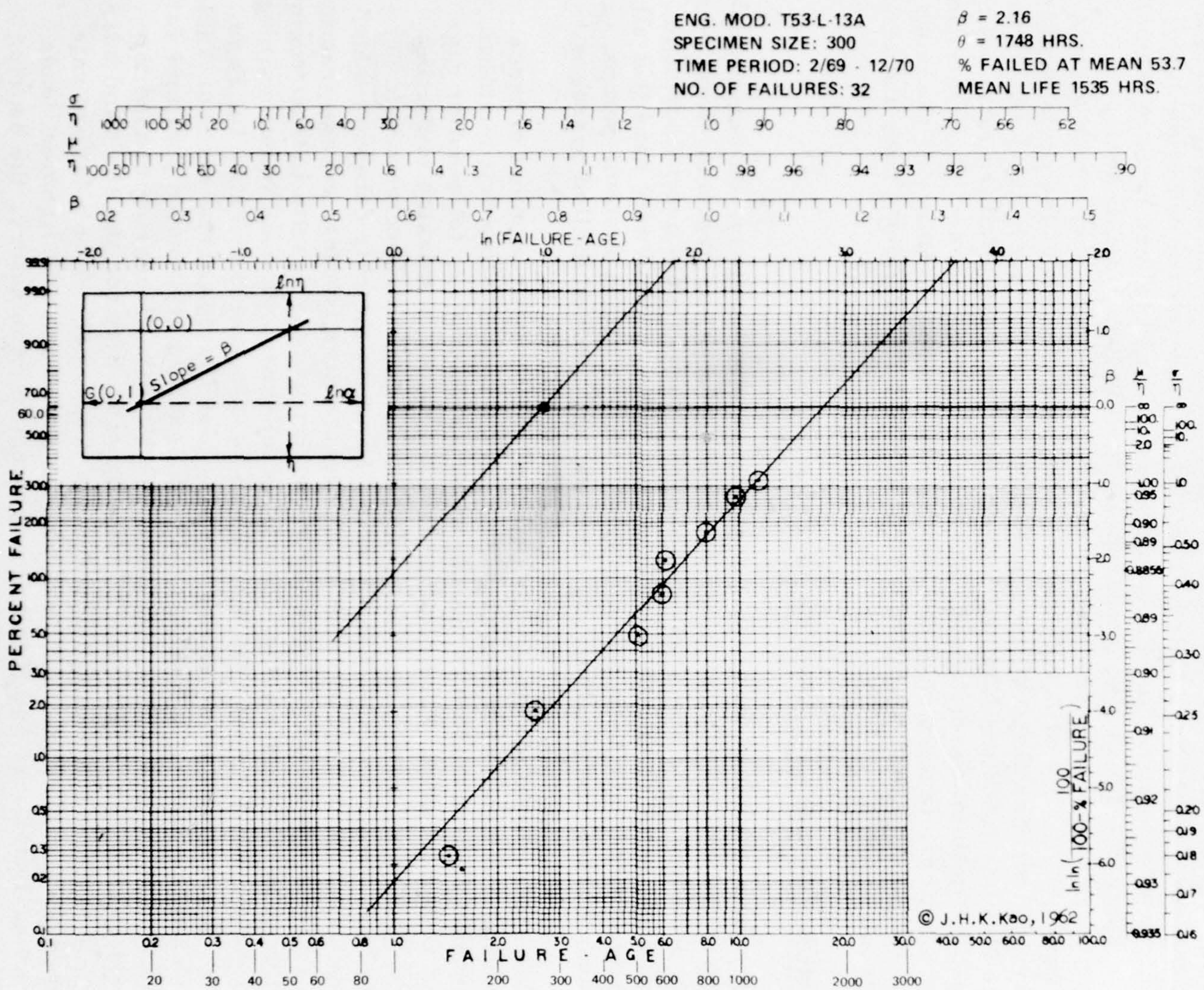


Figure 26. Weibull Plot - Number 2 Forward Seal

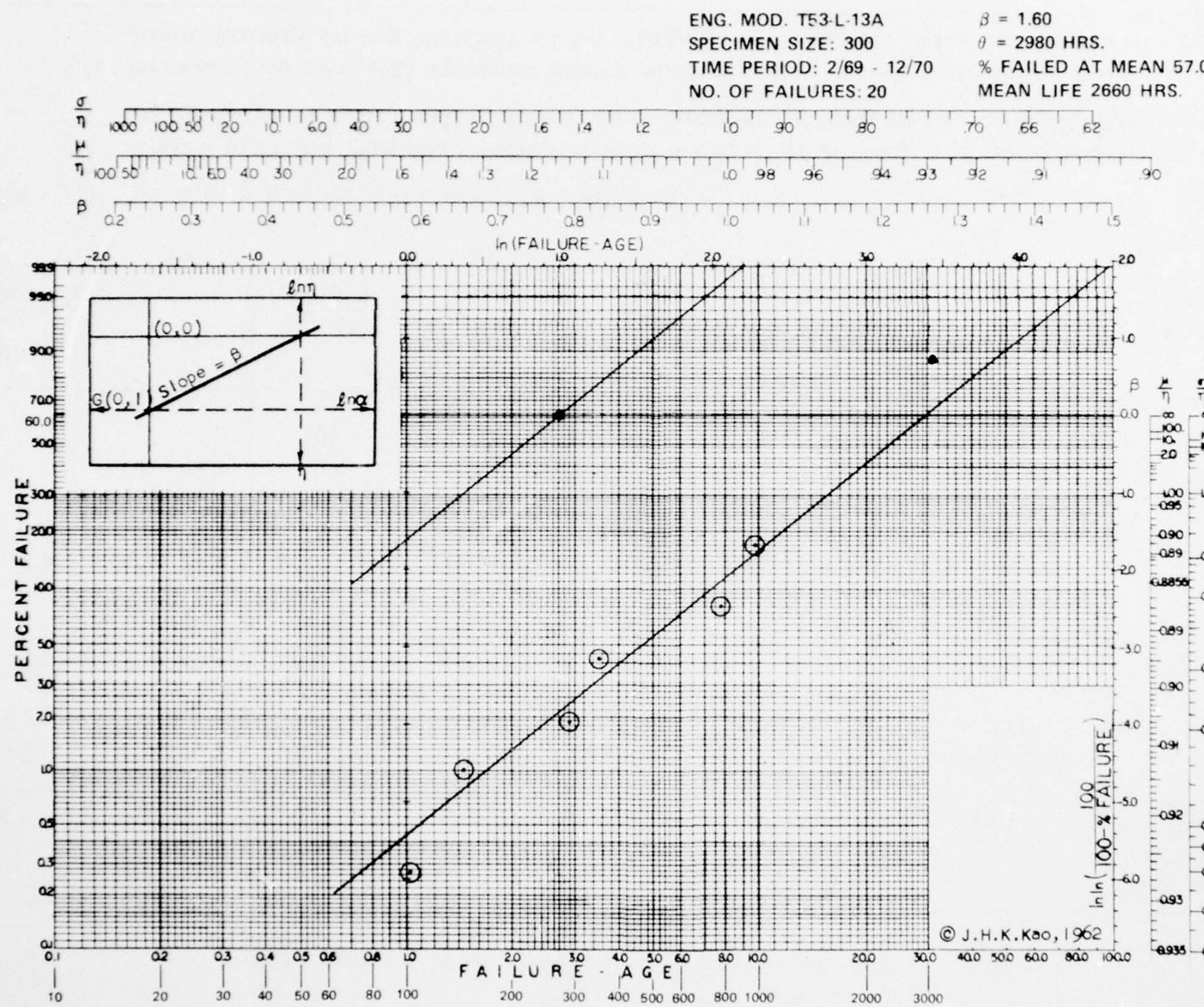


Figure 27. Weibull Plot - Number 1 Seal

Table 9. MTBF of Mainshaft Bearings

(1 January 1965 Through 31 December 1970)

Engine	Flying Hours	Mainshaft Bearings No. 1	No. 2	No. 3	No. 4	No. 21	Engine MTBF Due to Bearings
T53-L-7	730,955	182,740 (4)	40,610 (18)	1,462,000 (0.5)	76,940 (9.5)	146,200 (5)	19,755 (37)
T53-L-11	6,514,400	70,810 (92)	34,470 (189)	265,900 (24.5)	69,700 (93.5)	23,265 (280)	9,595 (679)
T53-L-13	5,724,405	150,650 (38)	98,700 (58)	409,000 (14)	79,500 (72)	38,420 (149)	17,295 (331)
T53-L-15	106,920	(0)	(0)	(0)	(0)	106,920 (1)	106,920 (1)
Composite Bearing MTBF		97,600 (134)	49,345 (265)	335,300 (39)	74,725 (175)	30,060 (435)	12,480 (1048)

NOTES: (1) Values in parenthesis are total failures.

(2) Where both the Number 3 and Number 4 bearings failed, and no assessment could be made as to which failed first, each bearing is scored as one-half a failure.

(3) Breaking up of metal sprayed power shaft bearing journal surface, with subsequent damage to the Number 21 bearing, is not considered a bearing failure.

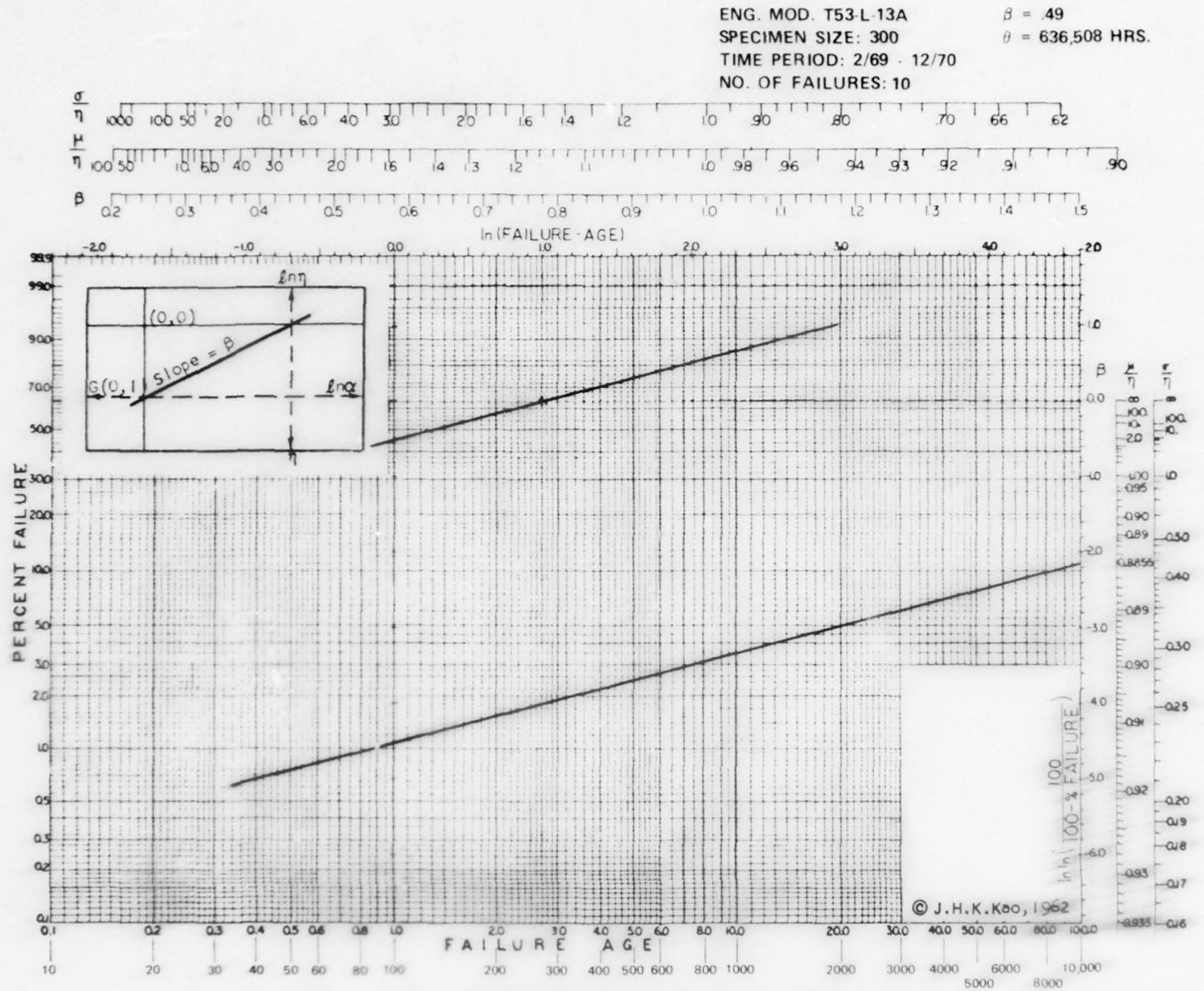


Figure 28. Weibull Plot - Number 21 Bearing

Number 21 Bearing - The problems observed in this position resulted from forced roller skewing. In particular, the function of the bearing is to support the power turbine shaft at a forward engine position. During operation, the bearing position shares support of the shaft with the power turbine bearing assembly and the power shaft power-transmitting sun gear. This redundance in support gives rise to misalignments at the Number 21 bearing location, and consequently to forced roller skewing. The roller skewing problems were manifested as retainer breakage in the T53-L-11 and roller end wear in the T53-L-13 engine. The retainer breakage problem was resolved on the T53-L-11 by strengthening the retainer design. The T53-L-13 roller end wear problem was virtually eliminated by incorporating improved controls in the skew restraint.

The problem encountered in the Number 21 bearing of the T53-L-13 engine is one of roller end wear. In most cases, the end wear is limited to a single roller, and ultimate failure results from retainer damage caused by the worn roller. Failure statistics indicate that the incidence of failure is the greatest during the first 200 hours of service operation and that, if this period is survived, a greater reliability is achieved.

Examination of failed bearings led to the conclusion that the failures were the result of skewing of the roller, which causes the bearings to move and the roller ends to slide against the outer ring shoulders. This condition can be created by shaft misalignment, improper geometry, or shaft excursions. In this engine application, it has been established that the roller end radius breakout-point dimension affects the rate of end wear.

An engineering change was processed to limit the end radius breakout and, consequently, limit the roller skew angle. This improvement in design of the Number 21 bearing, which allowed the increase in MTBD, required no change in the size of the bearing or its B_{10} life. This change, which resulted in a Lycoming P/N 1-300-082-01 Revision "D" bearing, was incorporated (October 1970) in Lycoming engines beginning with serial numbers LE 22802 for the T53-L-13B engines and LE 30112 for the T53-L-701 engines. These engines were closely monitored to evaluate the impact of the design change. The following are the results achieved for this block of engines from October 1970 through August 1972:

Number 21 Revision "D" Bearings (1-300-082-01)

Number of engines with Revision "D" bearings	985
Bearings exceeding 200 hours	569
Bearings exceeding 500 hours	248
Bearings exceeding 1,000 hours	20
Number of major overhauls on the (985) engines	47
Failures reported	0
Total flying hours accumulated on Revision "D" Bearings	307,400

The Revision "D" Bearing accumulated, as of August 15, 1972, over 300,000 hours without a failure. A total of 569 engines out of 985 in the sample being monitored, surpassed the historical 200-hour critical failure level. Prior history on bearings without this change showed that almost 50 percent of bearing failures occurred prior to 200 hours.

Aside from this group of engines that were monitored, the Revision "D" bearing was also installed in overhauled engines. As of June 1974, there were no known failures of this improved powershaft bearing with over 2 million hours service time. The MTBD on the bearings prior to Revision "D" had been 45,000 hours.

Number 2 Bearing - Engine return causes affecting this bearing are split between outer race spinning and roller end wear. The roller end wear problem was reduced by providing balanced forward and aft lubrication and cooling and by introducing a roller design change. The roller change consisted of concentricity and quality control of the roller end face-to-end radius junction. Pinning of the outer ring to prevent rotation is now being developed and is expected to be initiated in the T53-L-703 engine model. The pinning design is also being introduced in the Number 3 bearing to maintain commonality between the bearings used in both positions. A summary of Number 2 bearing configurations follows for engine models T53-L-11/13/15.

Lycoming Part Number	Vendor Identification Number	Description
1-300-013-04	5703	Bronze Cage - Staked Roller Pockets
1-300-013-04	5709	Bronze Cage - Controlled Roller Retention
1-300-013-04	5706	Increased Strength Bronze Cage - Controlled Roller Retention
1-300-013-05	457798	Silver-Plated, Steel Cage
1-300-176-01	5724	Bronze Cage - Controlled Outer Ring Thickness
1-300-176-02	461904	Steel Cage - Controlled Outer Ring Thickness
1-300-176-03	462642	Steel Cage With Roller End Controls
1-300-176-04	5728	Bronze Cage With Roller End Controls

Also contributing to the increased bearing reliability were changes made to the Number 2 bearing package which increased the oil scavenge flow for the T53-L-13 engines. The following tabulation shows the effect of these changes on the mean-time-between-bearing cage-failures. Figure 29 shows the improvement in mean-time-between-depot (MTBD), due to the reduction in bearing cage failures, for the T53-L-9, L-11, L-13/13A/13B engines.

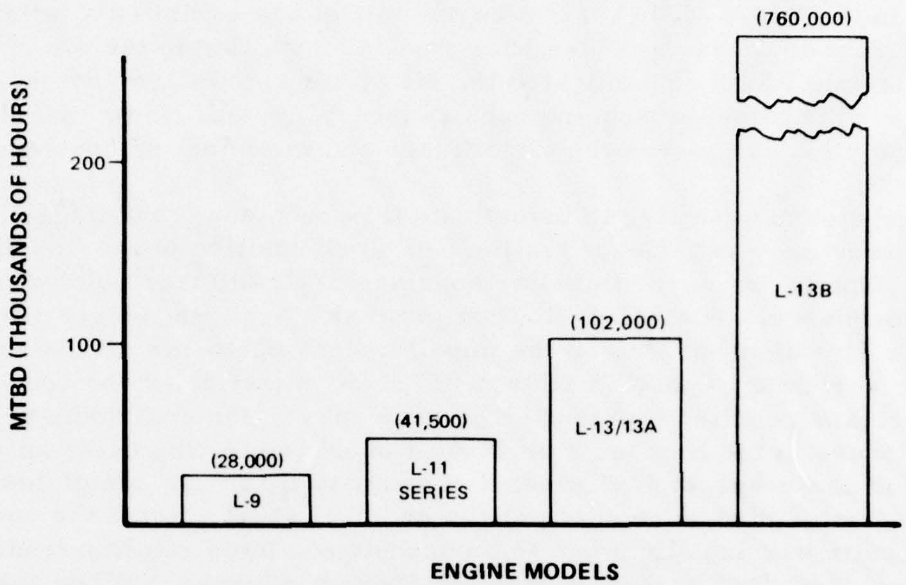


Figure 29. MTBD for T53 Number 2 Bearing Cage Failures

Number 2 Bearing Cage Failures

	Design Configuration	Engine Flying Hours	Mean-Time-Between-Bearing Cage-Failures(hr)
T53-L-13A	Original Configuration	1, 783, 375	78, 000
T53-L-13A	Engines With Increased Oil Scavenge Flow	2, 110, 065	96, 000
T53-L-13A	Engines With Increased Oil Scavenge Flow and New Bearings, Lycoming Part Number 1-300-176-03/04	1, 830, 970	141, 000
T53-L-13B	Engines Incorporating Lycoming Part Number 1-300-176-03/04 bearings and sawcut seals	3, 812, 000	760, 000

Position Number 2 Bearing Outer Race Rotation - The Number 2 bearing package in the T53-L-13/13A/13B engine model has exhibited a failure mode of Number 2 bearing outer race rotation resulting in the wearing away of metal, which contaminated the oil system. This problem had been associated with impeller housing rubs caused by loss of clamping bolt torque and pilot fit between the air diffuser and the impeller housings.

During development testing to investigate this problem, centrifugal compressor rubs were experienced at the 6-o'clock position of the impeller housing. Monitoring of the impeller housing-to-air diffuser bolts showed loss of torque when operating with compressor discharge temperatures of 625°F. Investigation showed the impeller housing-to-air diffuser pilot diameter shrinking, approximately 0.025 inch, misaligning the compressor rotor, and resulted in impeller housing rubs which contribute to abnormal forces in the Number 2 bearing. Endurance testing using an extended bolt and a spacer (for expansion compatibility) was completed. A detailed rotor clearance check at the end of the test showed the compressor main bearing alignment to be unchanged. Race rotation tendency then was turned "on" by misaligning the rotor and turned "off" by the use of this improved clamping configuration in the test cell. This improvement has been incorporated in the T53-L-701 and T53-L-13B engines.

Field experience showed the following improvement:

	Number of Engines Returned to Depot Due to Number 2 Bearing Outer Race Rotation	MTBD
T53-L-13A (No Fix)	130	49,500 Hours
T53-L-13B (With Fix)	34	112,000 Hours

Further improvements in the pilot fit of the compressor rear shaft reduced a possible shift in the rotor stackup. Incorporation of this improvement is expected to further reduce Number 2 bearing outer race rotation. Although the MTBD (due to Number 2 bearing outer race rotation) has more than doubled, outer race rotation has not been totally eliminated. However, a design to effect mechanical pinning of the Number 2 bearing outer race has been formulated and fabricated and is now incorporated into the T53-L-703 engine.

The increase in the mean-time-between-depot (MTBD) due to the reduction in cage failures and race rotation shown in Figure 29 and the above table resulted in an increase in the MTBD for the T53-L-13 series engines. This increase was from 34,483 hours for the T53-L-13A to 62,500 hours for the T53-L-13B. All of the operating hours with the T53-L-13B are with the new configurations, while the T53-L-13A had a mixed configuration.

Numbers 1 and 4 Bearings - The reported problem in Numbers 1 and 4 bearings has been retainer land wear and/or breakage occurring on the bearing side, opposite the lubricating oil jet. The bearings affected feature an inner-land piloted silver-plated bronze retainer. The inner-land piloting design, in conjunction with side lubricating oil jets on one bearing face, has been found to be sensitive to oil flow and oil direction anomolies. An outer-land piloting steel retainer design was found to have greater compatibility with the lubrication method used. The design has been released for the Number 4 location, and development activities are planned for its incorporation in the Number 1 location.

T55 Engine Bearing Problems

The following bearing problems relate to engine model T55.

Number 2 Outer Race Rotation - An antirotation pin was introduced to the T55-L-5/7/7C engines to prevent outer ring rotation. Newer versions of the T55 engine incorporate this change, e.g., T55-L-11 and LTC4B-8D.

Numbers 6 and 7 Bearing Outer Race Rotation - The bearings in this position are required to float axially within the housing to accommodate relative thermal growth between the outer structure and the shaft. This feature makes it difficult to adapt positive pinning, as it would impede axial floating of the outer ring. A design change has been incorporated in the LTC4B-8D to inroduce elastomeric O-rings in outer ring grooves. The friction imposed by the O-rings has been beneficial in preventing rotation wear.

Mechanical Torquemeter Bearing - The use of a single bearing in the cam follower of the mechanical torquemeter gives rise to a substantial cocking motion of the cam follower; this has caused retainer breakage in some bearings and rubbing of the cam follower face against the shaft shoulder in others. The rubbing problem was corrected by providing running clearance between the shaft shoulder and cam follower.

Compressor Rotor Problems

All of the engines returned to overhaul for compressor problems were associated with the T53 series engines that utilize a six-stage (five axial, one centrifugal) configuration. In the order of frequency, these problems are:

a. Fracture of the second- and fourth-stage discs (blade tenon area).

b. Fracture of a centrifugal impeller vane.

c. Fracture of centrifugal impeller attaching bolts.

d. Rupture of the second-, fourth-, and fifth-stage disc.

e. Compressor blade fatigue.

Most of the items listed above may result in a safety or mission-affecting event with no warning since these failure modes were not detectable with the maintenance or on-board diagnostics.

In general, these compressor problems can be separated into three groups:

a. Those compressor disc fractures and ruptures caused by increased operating stresses in uprated engine models.

b. Blade and impeller vane fractures associated with abnormal stress and vibration caused by inlet blockage or other engine components.

c. Noisy compressor operation during startup or shutdown periods due to fractured bolt(s) in a twelve-bolt impeller mounting circle. The bolt fractures were caused by vendor-material processing problems and did not result in in-flight shutdowns. However, since they were not field replaceable these did cause the engine to be depot returned.

The compressor problems are discussed as follows:

T53-L-13 Fourth-Stage Compressor Disc Tenon Failures - During 1969, a significant rise in the failure rate of T53-L-13 fourth-stage compressor discs occurred. Of 53 discs with confirmed tenon failures, 52 failed in Southeast Asia. Failure analysis on the 27 failed discs by the Materials Laboratories at Avco Lycoming revealed that these tenon failures occurred principally by a stress-rupture mechanism. Statistical analysis indicated that to forging and heat treatment lots of discs were particularly susceptible to early failures. these two lots were then retired from service. Other factors of a nonmetallurgical nature may have contributed to the premature tenon failures. The use of particle separators and environmental (air) conditioning un'ʼs placed additional demands upon the compressor and raised the possibility that engines were retrimmed in the field to maintain power. As a result, higher failure rates were experienced during the summer months. These possibilities suggest it is not always correct to assume that operation is in strict compliance with engine specification limits.

Metallurgical testing and examination of failed and high-time unfailed discs indicate that the coarse grain size in certain groups of discs was consistently relatable to the tenon failures. Rig tests of new coarse and fine-grained discs verified the increased strength of fine grain size. Previously, the significance of this parameter was not realized by the aluminum industry; this explains the absence of a grain-size requirement in the (disc) material specification (AMS 4135), which is used in a wide variety of applications throughout the aerospace industry. The new knowledge about the effects of grain size has led Avco Lycoming to specify fine-grained material from its forging vendors. Additional work has shown that alterations of forging grain flow provide further effects beneficial to disc life.

Figures 30 through 34 show the compressor rotor with the damaged fourth-stage disc together with surface fracture in the tenon area. Figure 35, a Weibull plot of the fourth-stage disc failures, indicates a slope of 1.20 or an increasing failure rate with respect to time.

A Product Improvement Program was initiated in 1963 to provide compressor components with increased strength, durability, and corrosion resistance by utilizing the superior characteristics of titanium. During 1963, a titanium compressor rotor was designed and fabricated to demonstate the potential improvements to existing assembly techniques, maintainability criteria, and environmental influences experienced by the rotor during its operation. This rotor design demonstrated, via 400 hours

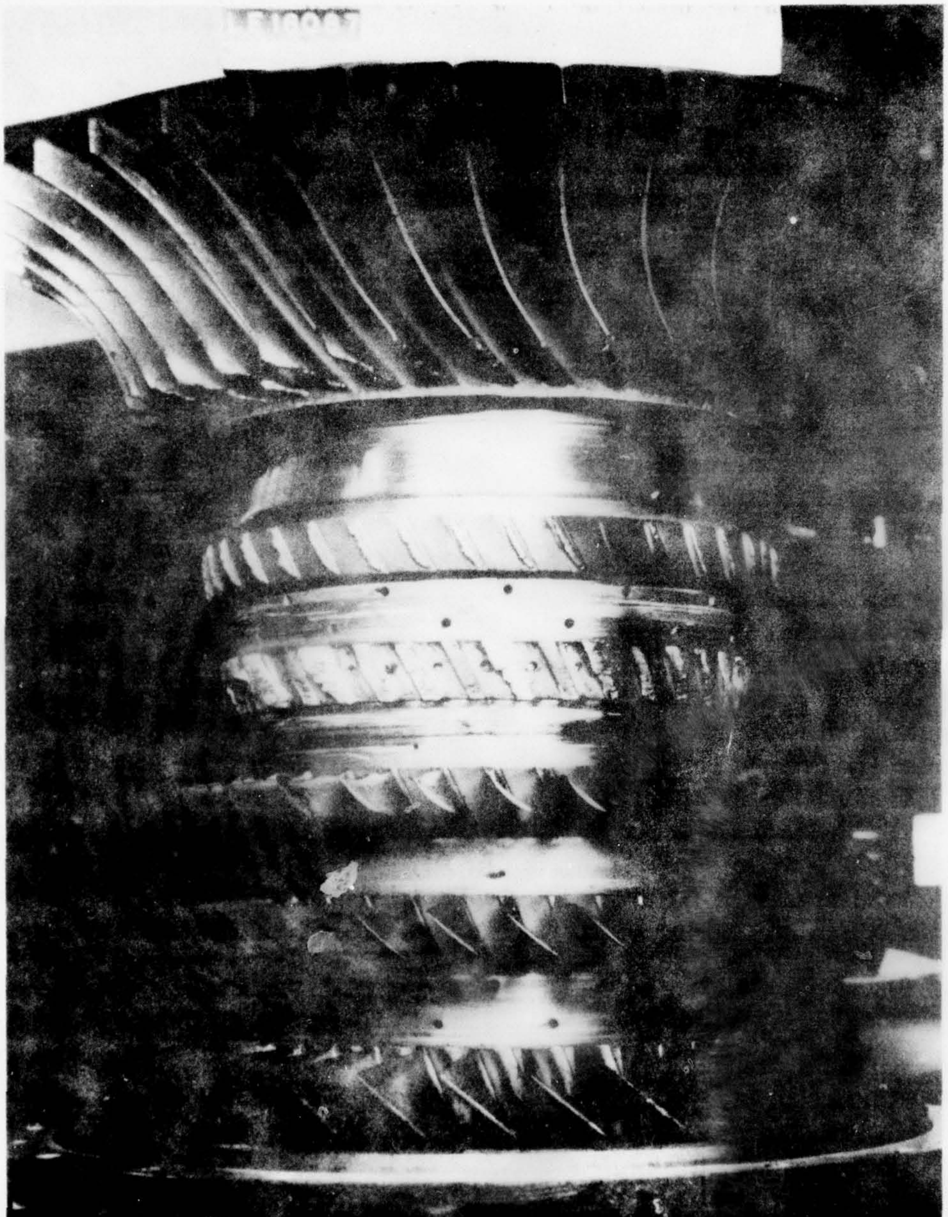


Figure 30. Typical T53-L-13 Compressor Rotor After Failure of the Fourth-Stage Disc

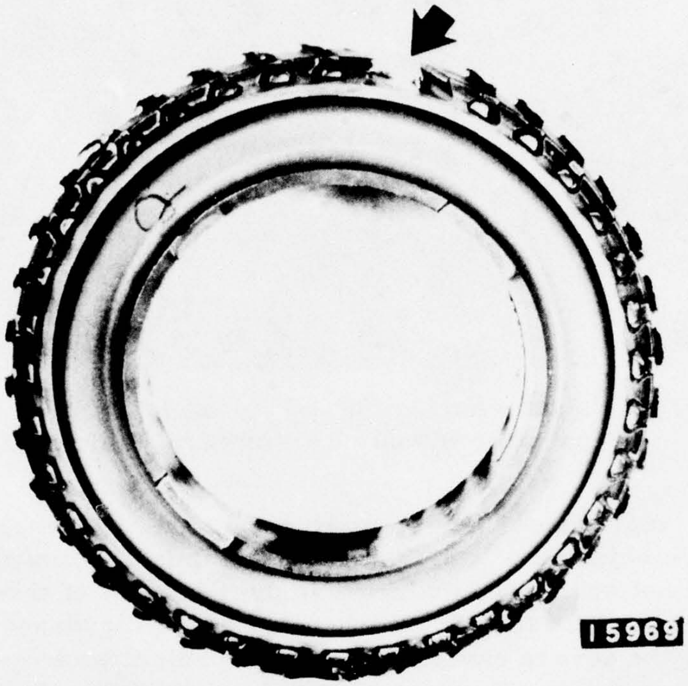


Figure 31. Front Overall View of a Fourth-Stage Compressor Disc Which Sustained Failure of a Single Tenon

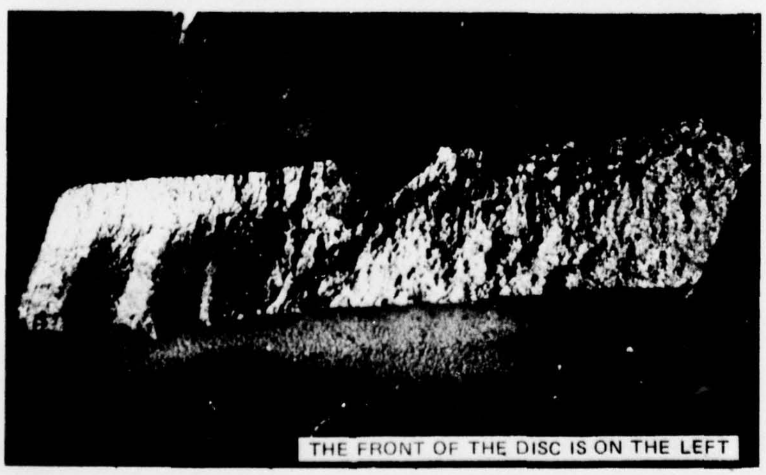
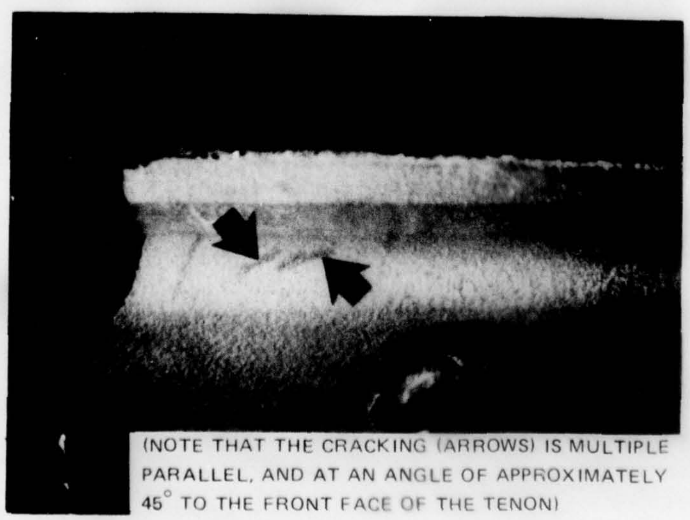


Figure 32. Fracture Surface of a Typical Tenon Which Was Completely Severed

Figure 33. Fracture Surface of a Typical Tenon Which Sustained Separation of Only Its Forward Position

of successful engine tests (accelerated aging and MQT engine cycles), that the design objectives had basically been met. Continuation of this program was not sponsored and further development of this design remained dormant. With the advent of engines with increased operating speeds and more severe environments, the project was re-initiated in 1967 to continue the development and evaluation of this design concept.



(NOTE THAT THE CRACKING (ARROWS) IS MULTIPLE PARALLEL, AND AT AN ANGLE OF APPROXIMATELY 45° TO THE FRONT FACE OF THE TENON)

Figure 34. Typical Cracked Tenon

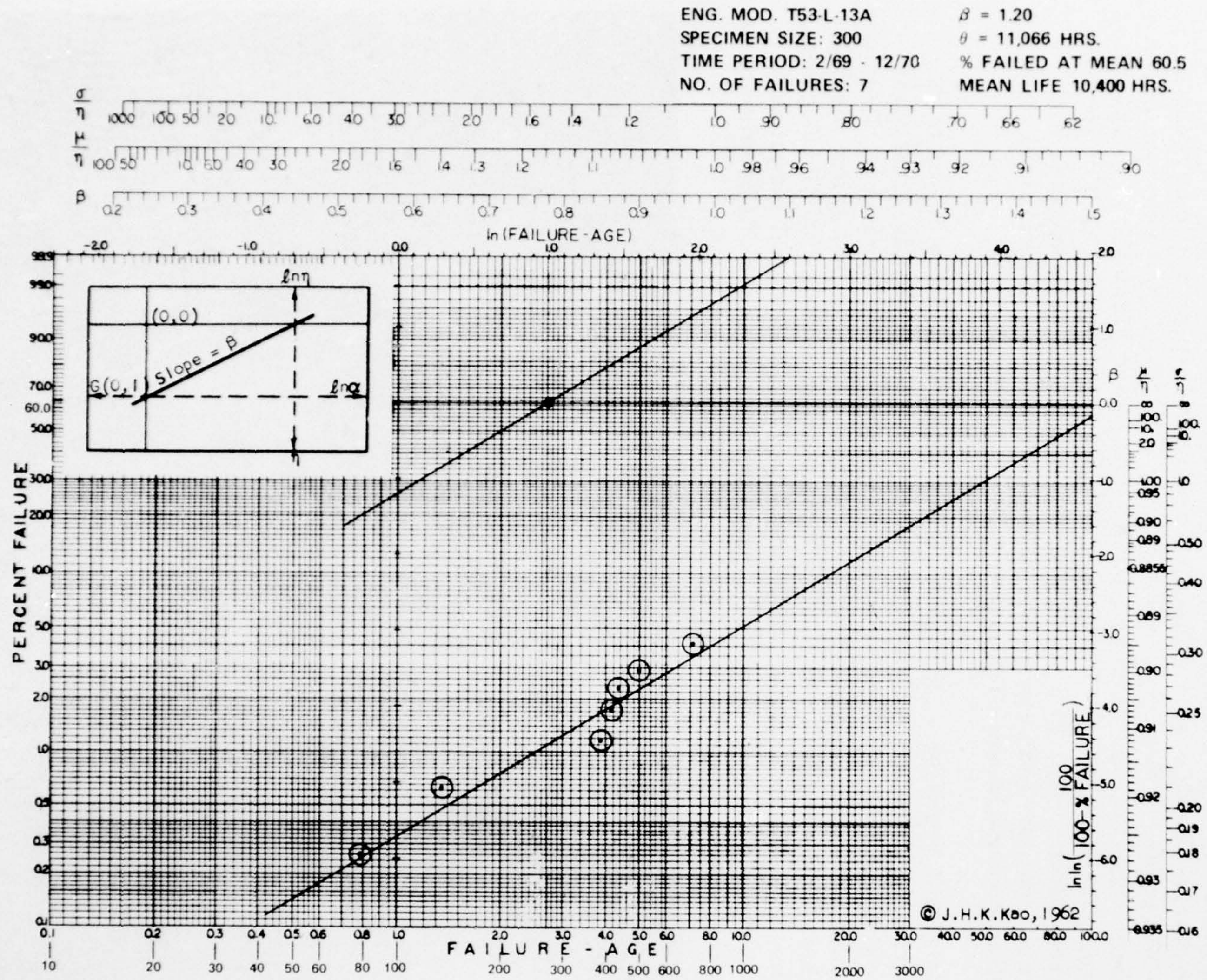


Figure 35. Weibull Plot of Compressor Fourth-Stage Aluminum Disc

The T53-L-13/13A field experience had shown that the second-generation type of gas turbine engine needed a stronger, more durable type of compressor rotor disc arrangement. Hence the titanium compressor discs were further developed and became the main feature of the current T53-L-13B engine. The change from aluminum to titanium discs resulted in a design strength improvement from 47,200 psi to 113,000 psi at operating temperatures. The T53-L-13A engine experienced an MTBD of 16,000 hours with the aluminum discs whereas the T53-L-13B engine, with titanium compressor discs (one-piece design), has accumulated over 3.8 million hours without a failure.

Centrifugal Impeller - During 1971, vane fracture of the T53-L-13B centrifugal impeller became a problem. The failure mode constituted cracking and/or complete breakout of a vane section by fatigue. Fracture origin was observed at approximately vane midspan, just above the fillet radius, at the concave surface of the vane (see Figure 36). Crack propagation took place along the vane length in both fore and aft directions. When complete section breakout was experienced, cracking terminated at the vane outer edge.

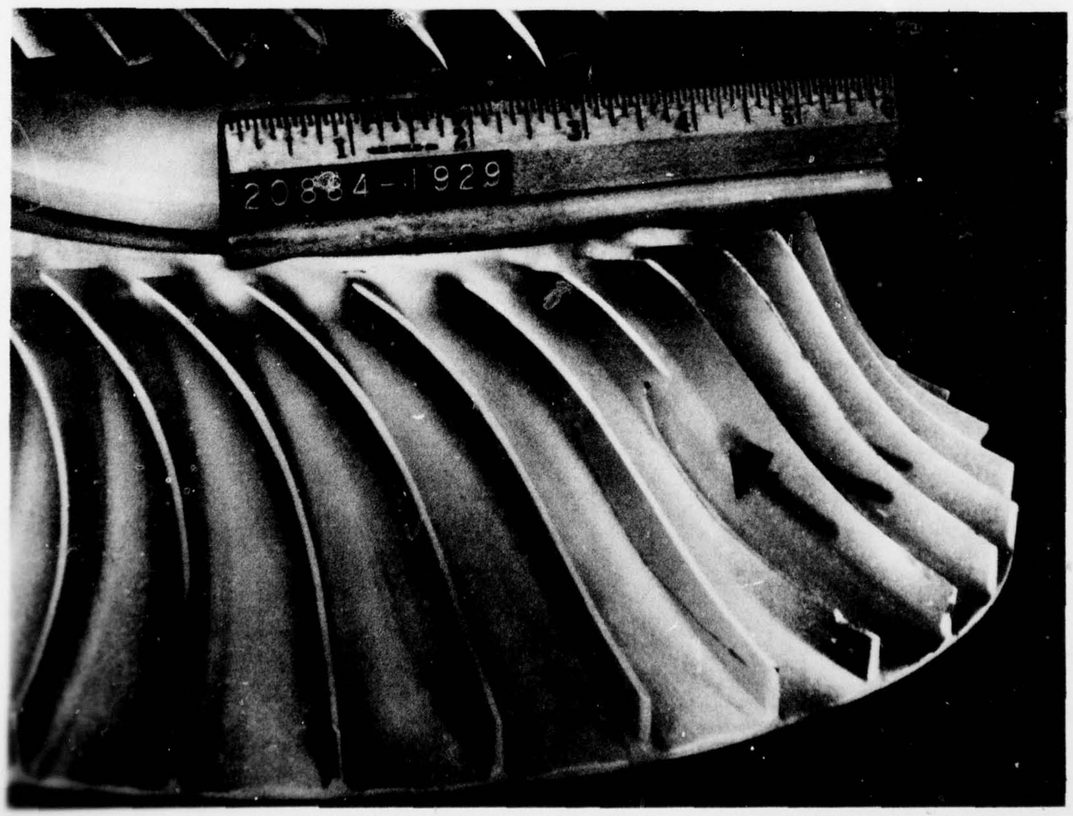


Figure 36. Centrifugal Impeller Showing Vane Damage

Most of the impeller failures were originally returned due to high EGT or surge. Teardown at depot revealed that the impeller failure and the data was changed to impeller-caused return.

An investigation into possible causes of the problem revealed:

a. Impeller resonance was occurring at N1 speeds of 92-104 percent. However, testing did not indicate stresses of sufficient magnitude to cause failure.

b. The exciting frequency was of the 28th order and was induced by the first row of 28 air diffuser vanes.

Additional vibration testing was performed to determine the natural frequencies in order to aid in the development of the final design configuration. The test showed that the standard vane had a natural frequency (third mode) of 10, 440 H, which is in close agreement with that measured during engine testing. It was this testing, plus the full engine testing, which prompted the increase in vane thickness to get the impeller resonant frequency beyond the normal engine operating range.

There is a significant difference between engine operation (mission profile) for the UH-1 and the AH-1G. A review of the mission profiles for each aircraft indicates that the AH-1G traverses the critical speed range more frequently than the UH-1; consequently, the resonant frequency of a specific impeller was reached more often during a typical AH-1G mission than during a typical UH-1 mission. For example, an impeller whose resonant frequency occurs at 94 percent N1 might experience a resonant condition only 6 to 7 times during a typical UH-1 (troop transport) mission, but as many as 26 or 28 times during an AH-1G (attack) mission. For this reason, the mean-time-between-failures for engines installed in the UH-1 was 2.4 times that for engines installed in the AH-1G (28, 000 hours versus 11, 594 hours), based on 811, 900 hours and 29 impeller failures in the UH-1 engines and 382, 600 hours and 33 failures in AH-1G engines.

A new thicker-vaned impeller was tested with successful results. The increase in vane thickness changed the natural frequency of the vane in a manner such that resonance was no longer experienced within the normal engine speed regime. In addition, Avco Lycoming Materials Laboratory testing determined that the average endurance strength of impeller vanes could be further improved by glass-bead surface peening. Impeller specimens with glass-bead peened aerodynamic surfaces displayed an increase in minimum high-cycle fatigue endurance limit as much as 70 percent. Consequently, in November of 1971 an improved impeller with increased thickness and glass-bead shot-peening was approved. Because of the long lead time required for castings, shot-peened thin-vane impellers were incorporated into the overhaul system in February 1972, and thick vaned impellers were introduced into the system in May 1972. Figure 37 shows the improved fatigue life with glass-bead shot peening.

Although there were over 360 engines with vane fractures reported on the original thin-vaned impeller, there have been only five shot-peened thin-vaned impeller fractures reported and there have been no failures reported on the thick-vane impeller.

Fifth-Stage Compressor Disc

Stress rupture was also the failure mode on the fifth-stage compressor disc on the T53-L-11 series engines. This disc, made from aluminum alloy, was also affected by the increased operating temperatures associated with the power demands and high ambient temperatures experienced in Vietnam. Like the T53-L-13A, the solution to this problem was the incorporation of a fifth-stage disc made of titanium. This change also incorporated a heavier fourth-stage spacer. Since the incorporation of these features, no further problems have been encountered.

Air Diffuser

The problems associated with the air diffuser are mostly due to air or oil leakage caused by cracks around vanes, transfer tubes, and fittings. These defects are not usually mission or safety impacting, but, because the air diffuser was not field replaceable, the engine had to be returned for overhaul.

Improvements in the air diffuser design included fitting attachment changes, an increase in parent material thickness, and improved welding techniques. In addition, the air diffuser was made field replaceable on T55 series engines.

Turbine Blades

Turbine blade failures were analyzed and failure modes were identified. The use of hollow-core blades to reduce weight and to provide cooling air passages introduces the possibility of casting or manufacturing variations reducing blade life. If a hollow core blade has a reduced wall thickness resulting from improper casting or inspection techniques, the stress levels in the remaining material are considerably higher than anticipated. The failure mode of these blades is usually identified as stress-rupture.

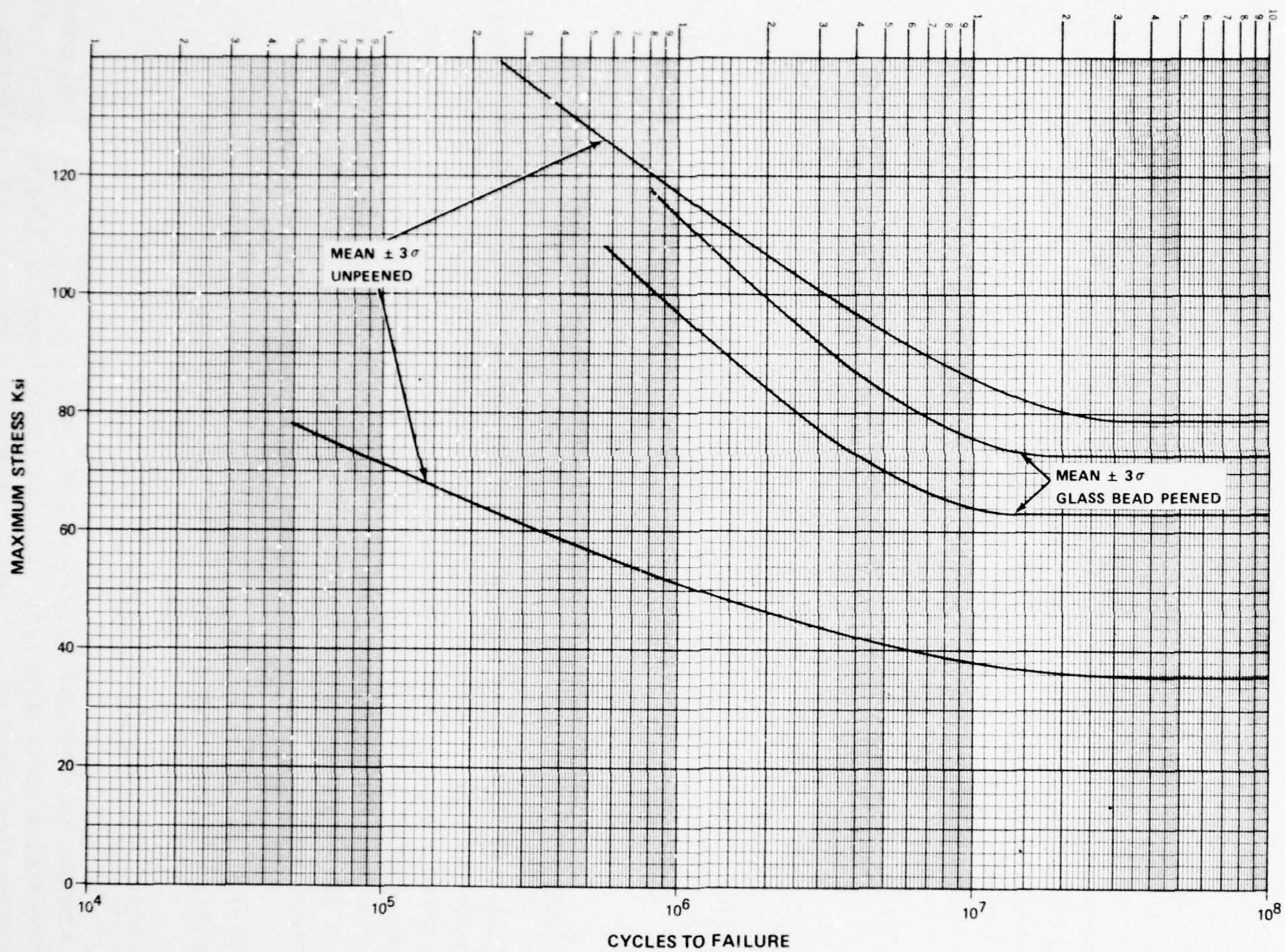


Figure 37. Centrifugal Compressor Fatigue Life

The use of improved monitoring processes and quality control techniques have been effective in minimizing this type of failure mode.

Another turbine blade failure with stress rupture as the failure mode was caused by abnormal combustion temperatures. These high temperatures are brought about by a variety of operator, operational, and maintenance factors. For example, an overtemperature condition may be caused by overtrim of the fuel control, either by ignorance or overzealous maintenance personnel in order to obtain more power from the engine. Abnormal starting temperatures due to low starter voltage (low battery) or dirty compressor, wrong fuel, and improper operator technique in the use of "manual mode" fuel control operation are the most common causes of turbine blade failure.

Although the composite turbine blade failure rate was 8.8 per million hours, practically all of the events were attributed to the T53-L-11B operation.

The turbine blade failure rate on the T53-L-13 series engines is much lower than on the T53-L-11 series even though operating temperatures are comparable and there are four turbines instead of two. This achievement was accomplished mainly by the use of improved high-temperature material.

Power Turbine Oil Impeller

Early T53-L-13B engines incorporated oil impellers to aid in the return of oil from the power turbine bearing package to the sump. These impellers were silver plated to minimize fretting of the contact surfaces. However, due to poor adhesion, the silver plate flaked and contaminated the oil system. Since several bearing cages were also silver plated, the source of this contamination could not be determined without complete engine disassembly. Hence, the engines were returned to depot.

The use of silver plate on these impellers was discontinued in favor of black-oxide coating, and no further problems were encountered.

Fuel Control Drive Spline Wear

During the period covered by this investigation, one T53-L-13 fuel control drive spline failure caused an emergency landing. The internal spline on the drive gear and fuel control male spline interface are subject to fairly high loads that cause wear unless some type of lubrication is provided. This situation is aggravated further by any misalignment of the components.

Previous T53 models used molybdenum disulfide lubricants that were applied during fuel control installation. However, with the increased load and higher fuel flow and pressure requirements of the atomizing fuel nozzles incorporated in the T53-L-13 series engines, the incidents of fuel control drive spline wear increased. The addition of a wet spline lubrication system using engine oil solved the problem. Since this change was incorporated, fuel control spline wear has been minimal, with most engines going through several TBO cycles without significant wear patterns on either the internal spline or the male gear.

Sun Gear Retaining Bolt and Washer - The planetary gear system used in the T53 reduction gear train incorporates a sun gear splined to the power shaft (see Figure 38). The sun gear is retained by a combination of spherical bolt and washer. If worn, this bolt and washer will allow the sun gear to move axially, thereby causing internal spline wear between the sun gear and the power shaft. Wear of the bolt and retainer was caused by inadequate lubrication and, to some degree, by mismatch between the two spherical surfaces. A revised lubrication system was incorporated by adding oil lubrication holes in the bolt and a nylon washer that replaced the previous bronze washer. Since incorporation of these changes, the sun gear spline wear problems have been eliminated.

REVIEW OF EXTENDED-SERVICE-LIFE TESTING

In-house extended-service-life (ESL) test data was reviewed to determine the effectiveness of existing test methods.

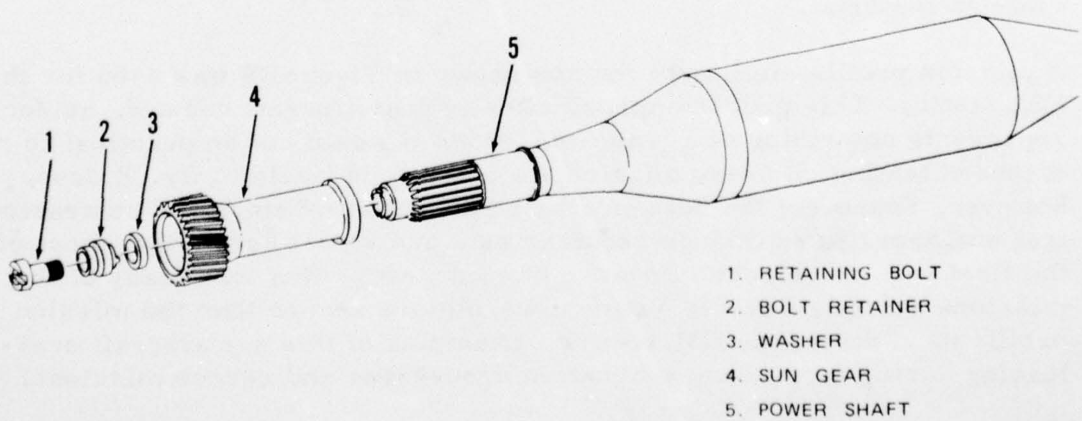


Figure 38. Sun Gear Retaining Bolt and Power Shaft Installation

This ESL testing included 17,600 hours of mission profile testing, 730 hours of forced failure testing, and 60,370 accelerated aging cycles. These tests were devised to simulate operation in a military aircraft and to subject the engine components to low-cycle fatigue excitation and to operating conditions in excess of current model specifications.

Table 10, summarizing this ESL test data, shows a strong correlation between test cell information and field returns in some areas, but less in others. ESL testing did reveal potential field problems for Number 2 bearing seal leaks, torquemeter bearing problems, and air diffuser cracking. However, bearing race rotation problems later discovered in field operation were not revealed during ESL testing.

The variance in rates may be due in part to the fact that several design changes were introduced during the early phases of testing, but were not always incorporated in production engines. This is particularly true in the case of the air diffuser cracks.

The bearing failure mode of race rotation did not manifest itself during the ESL testing. The absence of this failure mode can possibly be attributed to the low total number of hours accumulated, the small sample size, and the use of more experienced personnel assembling the test engines.

A review of T53-L-13A test data indicated that compressor disc stress rupture problems occurred in the test cell. Intermediate corrective actions included epoxy coating, shot-peening of the disc, and use of fine grain material. The final solution to this disc problem was the use of titanium material.

A mission profile similar to the one shown in Figure 39 was used for the ESL testing. This profile approximates typical aircraft use and, as such represents something of a trade-off, since it would not be practical to run extended testing on every mission the aircraft is likely to fly. It does, however, represent the best effort on the part of military and contractor test engineers to reproduce requirements and stress levels that most of the fleet will experience. Because of emergency situations many of the missions actually flown in Vietnam were more severe than the mission profile used during the ESL testing. Examples of this are aircraft overloading during emergency evacuation procedures and rescue missions.

Ideally, engine manufacturers prefer to run extensive tests at all speed and power settings and for all possible mission profiles; but in the past, time was at a premium, particularly in the case of the up-rated models of the T53 and T55 engines.

Table 10. Comparison of T55-L-7 Field Experience and Extended-Service-Life Test

Component	Field		Extended-Service-Life	
	Number	Rate x 10^6	Number	Rate x 10^6
Number 2 Bearing (Race Rotation)	70	136	0	0
Number 2 Seal				
Forward	95	185	3	170
Aft	69	134	3	170
Torquemeter Rotor	19	37	3	170
Number 6 or 7 Bearing (Race Rotation)	19	37	0	0
Air Diffuser Cracks				
Vanes	12	23	1	56
Weld Lines	4	7.8	3	170
Oil Pressure Fitting	20	39	0	0
Field Hours = 512,406				
ESL Hours = 17,600				

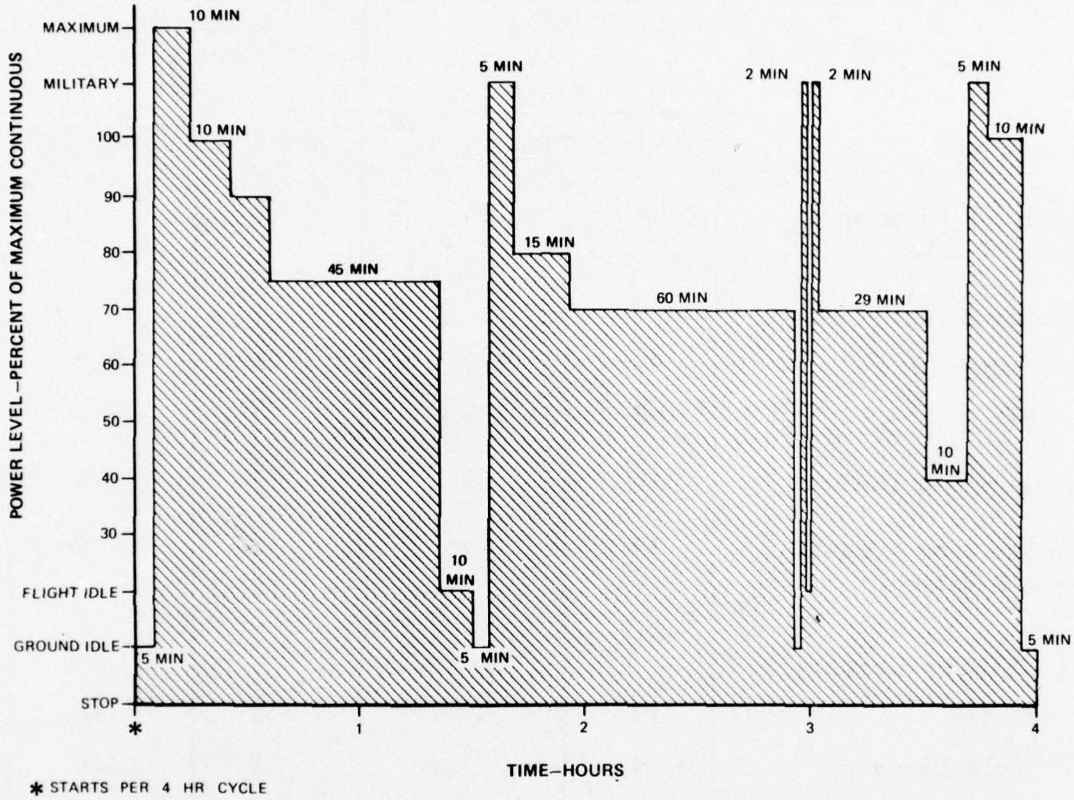


Figure 39. T55 Improved Reliability and Service Life Test Cycle

The practice now is to begin ESL testing in the test cell, which is then followed by continued testing in the airframe at Ft. Rucker, Alabama. Obviously, it is preferable to identify items that could cause premature returns before production is started. Conversion and modification programs, which are costly to implement, usually require that engines be returned before their scheduled TBO is reached. Often, though, there are strong pressures to verify the initial design concept so that long-lead items can be ordered for initial production, with the idea of fixing the minor problems later. Unfortunately, these minor problems that are known beforehand cause premature engine returns to overhaul.

REVIEW OF ENGINE-CAUSED RETURNS

Engines are usually returned to depot with a generalized *symptom* description. Teardown and analysis may provide the insight to identify a single component as the confirmed or suspected cause. Many of the engine symptomatic conditions described are representative of secondary engine damage. For example, bearing failures invariably result in contaminated lubrication systems; seal leaks result in high oil consumption or smoking; structural failure of compressor or turbine parts result in internal secondary damage; and a fuel control problem can result in an overspeed or overtemperature that requires an engine to be returned for a safety inspection.

The composite engine, viewed from the point of unscheduled necessary engine-caused returns, is shown in Figure 40.

The percentages of depot returns for the composite engine and returns and removal rates published in the T53 10-year report are listed in Table 11. Differences in the categories' percentages are probably caused by the smaller sample selected for the analysis, the engine models selected (*including commerical*), and the environment and time periods.

Oil Leaks and Consumption

Oil leaks and consumption relate to the seal failure modes discussed under engine-caused components. Leaks and consumption are the diagnostic indicators that maintenance personnel use to measure the condition of seals. In general, no specific data on individual seal leakage rates are specified. Maximum consumption rates for the total lubrication system are given in the field manuals.

Some effort has been made to measure seal leakage by using a test kit that has an electrically driven vacuum pump. When connected to the bearing package, through existing scavenge or pressure lines, the kit will provide an indication of the seal condition. This test must be done with the engine in a static condition and, therefore, is not always representative of dynamic seal conditions. This test kit is used in manufacturing testing and could be made available for field use.

Oil contamination is caused by metal particles in the lubricating oil system and is usually the result of abnormal wear on an oil-wetted component. In the case of the engines reviewed in this study, the component affected the most was the bearings, although gears and spline wear did account for a few returns. It is generally recognized that the Spectrometric Oil

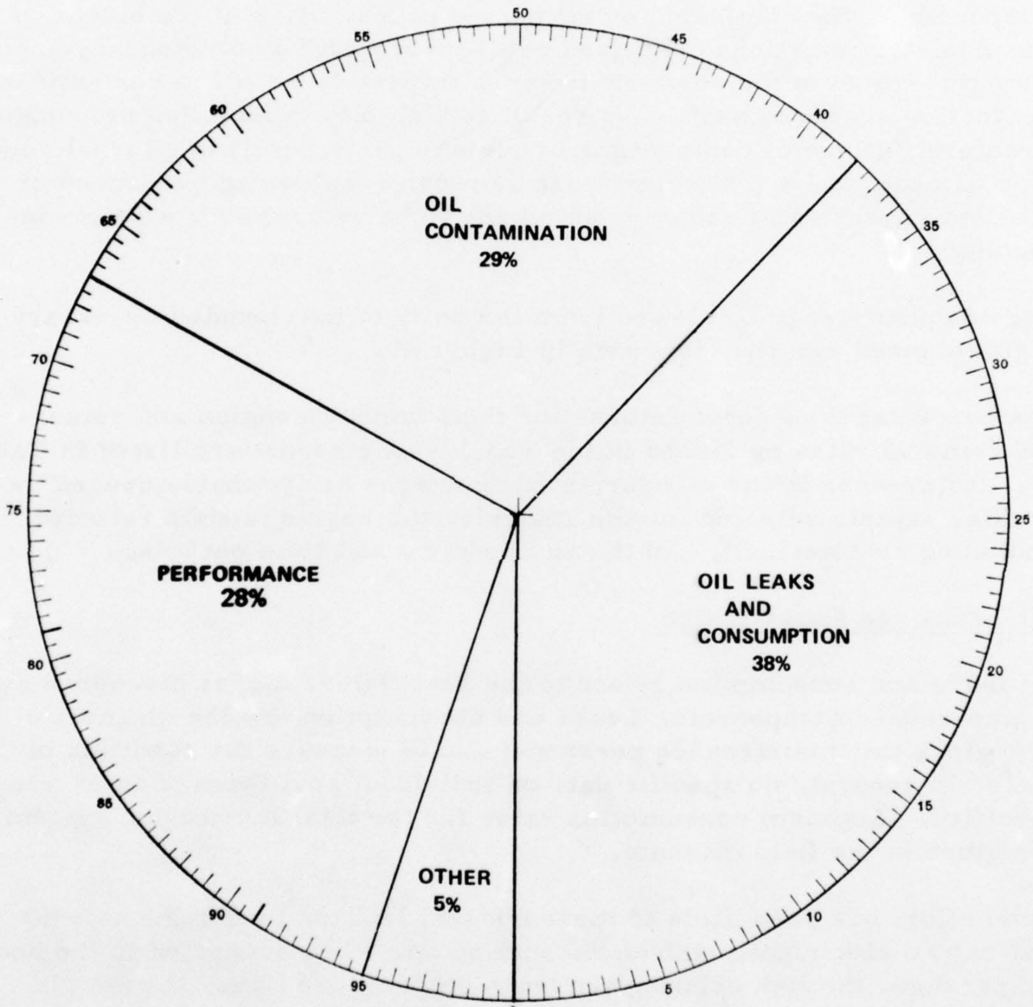


Figure 40. Composite Unscheduled, Necessary Engine-Caused Symptomatic Inspection Returns

Table 11. Engine Symptomatic and Inspection-Caused Returns

	Engine Returns (10-Year data)[2] (%)	Selected Engine Groups of TBO Study (%)
Oil Leaks/Consumption	50	38
Oil Contamination	14	29
Performance	30	28
Other	6	5

Analysis Program (SOAP) has the capability to detect worn or defective moving parts, such as bearings, gears, splines, etc. Excessively high or increasing levels of metal in the oil could indicate that heavy wear or spalling has occurred. Therefore, the engine is in need of at least an inspection, or perhaps an overhaul. Chip detectors, which are capable of picking up larger metal chips in the oil flow paths, can indicate that dynamically stressed parts are spalling or fracturing.

REVIEW OF ENGINE/SYSTEM DIAGNOSTICS

Spectrometric Oil Analysis

Since 1 January 1972, 51 T55 engines were removed from aircraft for depot returns as a result of SOAP (see Table 12). All of these engines have been analyzed at the Corpus Christi Army Depot (CCAD), as of 31 March 1975. Beginning 1 April 1975, Lycoming Reliability/Maintainability (R&M) overhaul personnel, who were on site, began identifying those engines considered to be SOAP candidates. An engine is classified as a SOAP candidate when teardown analysis at the depot reveals any discrepancy that should have been detected through SOAP oil analysis, even though the engine was not reported as being returned to the depot because of SOAP. For the nine months ending 31 December 1975, 18 T55 engines shipped to the depot were SOAP returns or candidates. Figure 41 illustrates the component causes found on these 18 engines.

[2] J. Lipnickas, T53 Reliability and Maintainability Evaluation Progrom, Avco Lycoming, Report Number 1628.5.15, U.S. Army Aviation Systems Command, St. Louis, Missouri, November 1974.

Table 12. SOAP Engines Returned to Depot
(1 January 1972 through 31 March 1973)

ENGINE MODEL	ENGINE S/N	TTSN	TSMO	DATE REMOVED	RECEIVED FROM	DATE RECEIVED	DATE SHIPPED	CAUSE COMPONENT
T55-L-7	01041	1832	0162	02/04/72	Ft. Rucker	02/01/72	12/19/72	Bearings, Numbers 6 and 7
T55-L-7	04271	1963	0210	01/30/74	R. V. N.	11/13/74	12/30/75	Gear, Accessory Drive
T55-L-7	04733	1833	0248	07/30/73	Ft. Rucker	09/18/73	10/29/73	Cause Unknown (Engine Scrapped)
T55-L-7	04849	1045	----	02/08/73	Texas, N. G.	03/14/73	12/30/75	Bearings, Numbers 4 and 5
T55-L-7	04876	2042	0321	01/10/74	Texas, N. G.	11/0175	12/09/75	Gear, Starter Drive
T55-L-7	04925	2522	0067	10/30/74	N. C. A. D.	11/05/75	12/01/75	Cause Unknown (Engine Scrapped)
T55-L-7	04937	1888	0302	10/12/72	Ft. Wainwright	12/12/72	11/06/74	Gear, Starter Drive
T55-L-7B	05625	1921	0156	02/17/74	R. R. A. D.	10/01/74	10/29/75	Cause Unknown-Not Engine Attrubutable
T55-L-7C	01074	1765	0254	05/12/72	R. V. N.	07/28/72	10/19/72	Oil Filler Sleeve (Imp. Installation)
T55-L-7C	01076	1985	0519	06/20/73	Ft. Hood	04/01/74	09/23/74	Bearings, Numbers 6 and 7
T55-L-7C	01088	2228	0468	04/09/74	Ft. Hood	09/29/75	03/16/76	No Problem Found
T55-L-7C	01103	2183	0105	01/11/72	Ft. Hood	02/16/72	05/05/72	Bearings, Numbers 6 and 7
T55-L-7C	01106	2155	0536	04/09/74	Germany	09/10/74	04/10/75	Nut Spur Gear Retainer (Imp. Installation)
T55-L-7C	01153	2272	0211	08/27/72	R. V. N.	09/21/72	12/05/72	Cause Unknown
T55-L-7C	01154	2437	0406	10/15/75	Ft. Sill	10/15/75	12/01/75	No Problem Found
T55-L-7C	03204	1344	0282	06/23/74	Ft. Hood	12/05/74	06/24/75	Bearings, Numbers 6 and 7
T55-L-7C	03268	0838	0100	06/25/72	Ft. Sill	02/05/73	04/04/73	Bearings, Numbers 6 and 7
T55-L-7C	03289	1407	0266	01/24/72	R. V. N.	02/28/72	06/12/73	Bearing, Number 2
T55-L-7C	03304	1248	0615	12/01/72	Ft. Sill	04/06/73	07/23/73	No Problem Found
T55-L-7C	03327	1154	0200	07/24/73	Ft. Bragg	10/05/73	03/15/74	Bearings, Numbers 6 and 7
T55-L-7C	03339	2056	0030	08/22/74	Germany	12/17/74	06/09/75	Bearings, Numbers 6 and 7
T55-L-7C	03401	0795	0235	09/10/74	Iowa, N. G.	01/30/75	07/18/75	Bearings, Numbers 6 and 7
T55-L-7C	03405	1491	0364	06/13/72	Ft. Sill	09/25/72	01/12/73	Cause Unknown
T55-L-7C	03431	1703	0307	06/17/75	Ft. Sill	03/01/76		Gear and Shim Accessory Gearbox
T55-L-7C	03486	1345	0226	09/26/72	Ft. Hood	11/02/72	02/15/73	Bearing, Number 3 (Imp. Installation)
T55-L-7C	03507	1124	0056	09/23/72	R. V. N.	11/13/72	03/01/73	Gear, Overspeed Drive
T55-L-7C	03516	1001	0773	04/15/73	Ft. Rucker	05/09/73	11/26/73	No Problem Found

Table 12. SOAP Engines Returned to Depot (Continued)
(1 January 1972 through 31 March 1973)

ENGINE MODEL	ENGINE S/N	TTSN	TSMO	DATE REMOVED	RECEIVED FROM	DATE RECEIVED	DATE SHIPPED	CAUSE COMPONENT
T55-L-7C	04138	3022	0280	01/22/75	N. C. A. D.	07/28/75		Bearings, Numbers 6 and 7
T55-L-7C	04168	2017	0736	01/29/72	R. V. N.	05/20/72	06/27/72	Bearings, Numbers 6 and 7
T55-L-7C	04191	2559	0268	01/04/72	Germany	05/09/72	07/12/72	Cause Unknown
T55-L-7C	04234	3303	0832	05/05/75	Ft. Rucker	03/01/76		Rotor, Torquemeter
T55-L-7C	04246	1844	0364	10/09/73	Ft. Hood	11/05/73	04/04/74	Bearing, Number 2
T55-L-7C	04328	2130	0949	06/28/72	Ft. Rucker	07/31/72	10/24/75	Bearings, Numbers 6 and 7
T55-L-7C	04340	2952	0410	08/07/73	Ft. Campbell	03/12/75	10/09/75	Bearings, Numbers 6 and 7
T55-L-7C	04360	1857	0638	10/19/72	Ft. Rucker	11/14/72	01/10/73	Bearing, Number 6
T55-L-7C	04362	1824	0020	02/03/73	R. V. N.	03/27/73	07/12/73	Bearing, Torque Drive
T55-L-7C	04469	1906	0003	06/21/73	Germany	08/16/72	12/15/72	Nut Pinion (Imp.Installation)
T55-L-7C	04474	1304	0093	03/09/73	R. V. N.	06/25/73	09/25/73	Cause Unknown
T55-L-7C	04583	1493	0489	03/01/73	Ft. Wainwright	06/20/74	02/12/75	Bearings, Numbers 6 and 7
T55-L-7C	04596	1799	0279	02/16/72	R. V. N.	03/04/72	06/06/72	Accessory Gear Box (Imp. Installation)
T55-L-7C	04742	1719	0406	10/16/73	Ft. Wainwright	06/20/74	02/25/75	Bearings, Numbers 6 and 7
T55-L-7C	04854	1808	0437	10/26/73	Ft. Rucker	11/01/73	03/01/74	Bearings, Numbers 6 and 7
T55-L-7C	04885	2647	1093	03/21/75	Ft. Wainwright	06/12/75	10/29/75	Bearings, Numbers 6 and 7
T55-L-7C	04943	4448	0783	05/22/72	R. V. N.	06/28/72	11/29/72	Bearing, Number 3
T55-L-7C	05606	1801	1023	02/16/72	R. V. N.	03/04/72	06/27/72	Bushing, P. T.
T55-L-11A	19325	0115	----	03/12/74	Germany	02/22/75		No Problem Found
T55-L-11A	19589	0964	----	12/12/72	Ft. Rucker	01/21/72	09/13/73	Bearings, Numbers 4 and 5
T55-L-11ASB	19140	0591	0400	09/24/75	Germany	03/01/76		Bearing, Number 49
T55-L-11ASB	19200	0586	0263	01/25/76	Korea	04/09/76		Bearings, Numbers 6 and 7
T55-L-11ASB	19204	0417	0173	09/15/75	Germany	03/01/76		Support, Bearing Number 1 (Improper Installation)
T55-L-11ASB	19306	0124	0116	07/18/75	Germany	10/15/75		Bearing, Number 1

AD-A042 190 AVCO LYCOMING ENGINE GROUP STRATFORD CONN STRATFORD DIV F/G 5/1
INVESTIGATION OF FACTORS CONTROLLING ENGINE SCHEDULED OVERHAUL --ETC(U)
MAY 77 P A KING, R L GIVENS DAAJ02-75-C-0018
UNCLASSIFIED LYC-76-42 USAAMRDL-TR-77-9 NL

2 OF 2
AD
A042190

END
DATE
FILMED
8-77

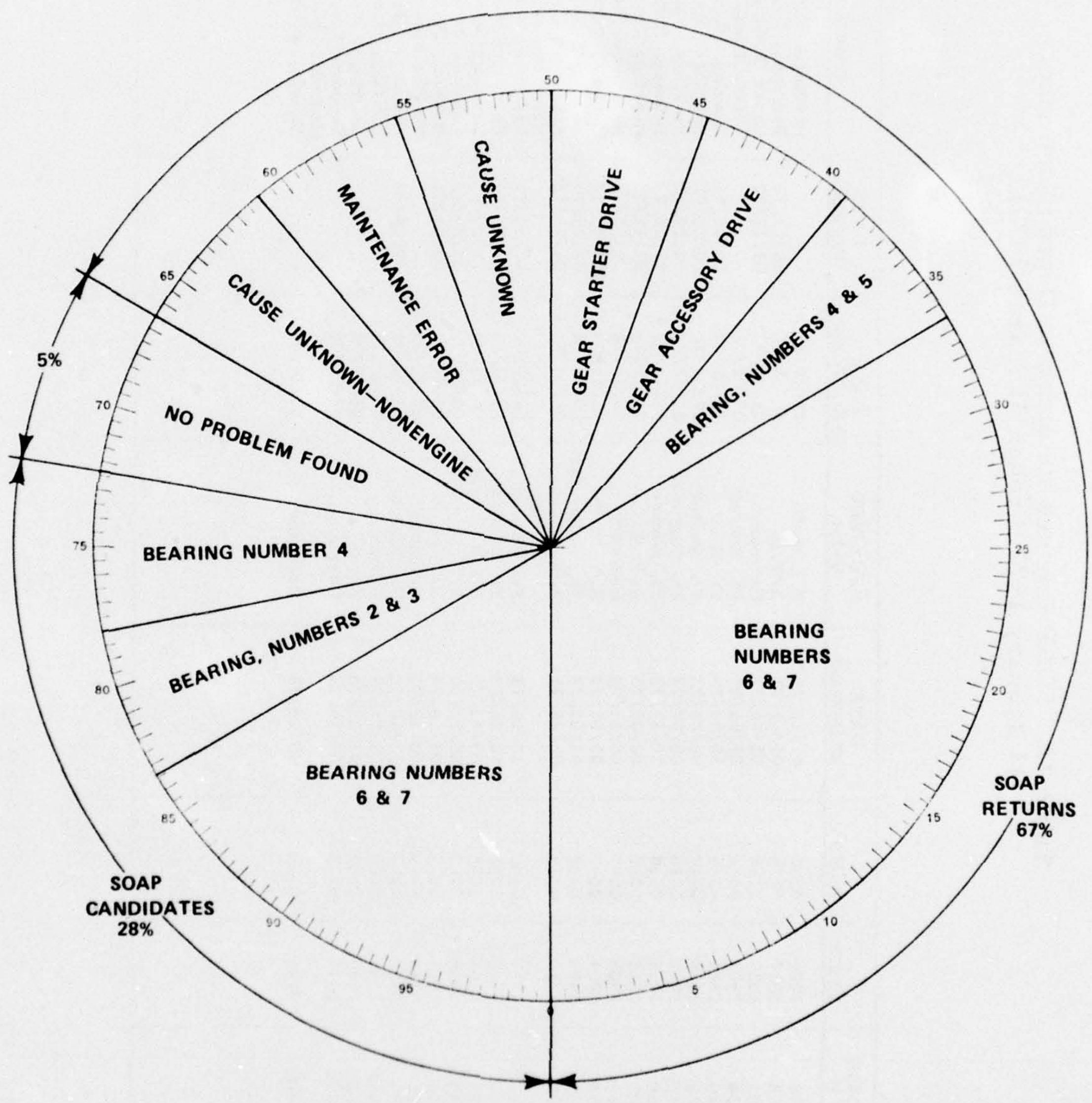


Figure 41. SOAP Returns or Candidates - Causes Found, T55 Engines (1 April 1975 through 31 December 1975)

Table 13 identifies those five engines that were classified as SOAP candidates. Figure 42 graphically portrays the causes found by onsite R&M personnel for these same 51 SOAP engines. Figure 42 shows that over 49 percent of all returns analyzed were the result of main shaft and Numbers 6 and 7 bearing failures. The data shown in Table 12 indicates that bearings were the most common problem, particularly rotation of the Numbers 6 and 7 bearing race. As discussed earlier, this duplex bearing supports the output shaft. This bearing's outer race is allowed to move axially to accommodate the differential thermal growth of the engine and power shaft.

The second most frequent cause of SOAP-detected engine problems was the result of improper installation or assembly techniques.

In an effort to establish a correlation with known bearing failures, the T53-L-13B engine returns for 1973 were reviewed for Numbers 1 and 21 bearing failures and then cross-checked for SOAP, chip detector indications, and metal particles on the main oil filter screens. As shown in Table 14, there were many engine returns whose records did not include data regarding SOAP, chip detector, and filter indications. In most cases, the chip detector and filter contained particles. A further check of those engines returned, due to SOAP sample readout, revealed that only a single Number 1 bearing and no Number 21 bearings were returned due to SOAP sample (refer to Table 15).

Although the SOAP program does predict some safety-of-flight failures prior to catastrophic failure, it also causes the return of many engines whose potential failure mode is not related to safety-of-flight. It is beyond the scope of this report to determine the cost-effectiveness of the SOAP program. Nevertheless, analysis[3] has shown that:

a. The SOAP Program has shown itself to be 67 percent effective in identifying actual problem engines in the field (see Figure 41).

b. 28 percent of the engines that SOAP should have identified in the field were returned to overhaul depot for other reasons (see Figure 41).

c. 89 percent of those engines returned to depot for exceeding SOAP limits were found to have oil system discrepancies which justified their return to depot (see Figure 42).

---

[3] R. Cardinale, T55 Reliability and Maintainability Quarterly Progress Report, Avco Lycoming, Report Number 1755.5.37, U.S. Army Aviation Systems Command, St. Louis, Missouri, March 1976.

Table 13. SOAP Candidate Engines Shipped to Depot
(1 April 1975 Through 31 December 1975)

Engine Model	Engine S/N	TTSN	TSMO	Date Removed	Received From	Stated Reason Returned	Overhaul Depot Findings
T55-L-7C	LE01066	1444	0454	06/26/74	N. C. A. D.	No defect scheduled mainte-nance	Bearings Numbers 6 & 7 spinning on shaft and liner. Bearing Number 2 spinning in housing. Metal chips found on magnetic plug and oil filter
T55-L-7C	LE03318	1417	0698	05/09/74	N. C. A. D.	Tempera-ture in-correct high EGT	Bearing Number 41 in Accessory Gearbox failed. Slivers of metal found under front cover
T55-L-7C	LE03378	1751	0375	04/03/74	Ft. Camp-bell	Ferrous metal re-peatedly found on mag plug	Bearings Numbers 6 & 7 spinning - Ferrous metal chips on mag plug and in oil filter
T55-L-7C	LE04790	2831	0561	02/21/75	N. C. A. D.	No defect scheduled mainte-nance	Bearings Numbers 6 & 7 spinning - Ferrous particles found in oil filter and oil tank
T55-L-7C	LE04938	1656	0818	07/31/74	R. R. A. D.	No defect scheduled mainte-nance	Bearings Numbers 2 & 3 spinning - Ferrous flakes and chips on mag-netic plug and oil filter

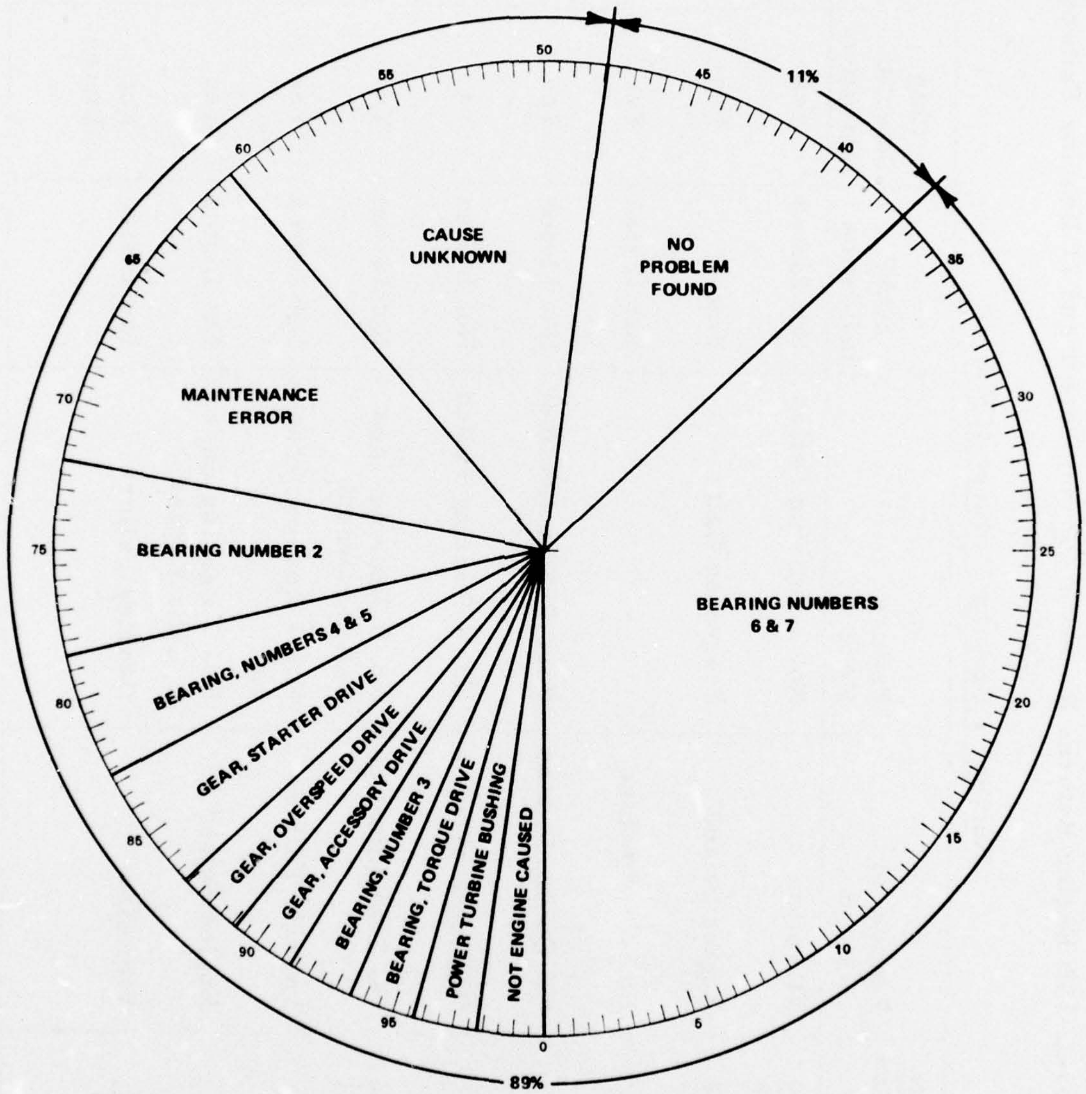


Figure 42. SOAP Engine Returns - Causes Found
(1 January 1972 Through 31 March 1976)

Table 14. T53-L-13B Engine Returns Reviewed for Numbers 1 and 21 Bearing Failures - SOAP - Chip Detectors

Number 1 Bearing Failures (1973)

Engine S/N	TSN* / TSO** (hr)	Reason for Return	Failure Mode	SOAP Indication	Chip Detector Indication	Filter Indication
14397	1914 / 128	Vibration	No. 1 Bearing Failed	Not Listed	Yes	Yes
16215	2842 / 722	Engine Seized	Scores on Balls	Yes	Yes	Yes
17144	509 / 61	Noise & Smoking	-	Not Listed	Yes	Yes
21849	971 / 355	Oil Contamination	Race Rub on Retainer	Not Listed	Yes	Yes
22349	732 / 006	Oil Contamination	No. 1 Bearing Failed	Not Listed	Yes	Yes
22571	1316 / 1161	Oil Contamination	No. 1 Bearing Cage Failure (Worn)	Not Listed	Yes	Yes
22744	193 / 153	Internal Failure	No. 1 Bearing Hous-ing	Not Listed	Yes	Yes
23038	455	Engine Seized	No. 1 Bearing Cage & Balls Frozen	Not Listed	Yes	Yes
15466	202 / 405	Vibration	Bearing Failure	Not Listed	Not Listed	Yes

Table 14. T53-L-13B Engine Returns Reviewed for Numbers 1 and 21 Bearing Failures - SOAP - Chip Detectors (Continued)

Number 1 Bearing Failures (1973)

Engine S/N	TSN*/TSO** (hr)	Reason for Return	Failure Mode	SOAP Indication	Chip Detector Indication	Filter Indication
21672	1380/1079	Oil Contamination	No. 21 Bearing Journal and Retainer Worn	Not Listed	Not Listed	Not Listed
23088	1011/0	Oil Contamination	No. 21 Bearing Cage	Not Listed	Not Listed	Yes
23413	882/0	Internal Failure	Bearing Failed	Not Listed	Yes	Yes

*TSN = Time Since New
**TSO = Time Since Overhaul

Table 15. T53-L-13B SOAP Samples - Oil Contamination (1973)

Engine S/N	TSN* / TSO** (hr)	Component	Failure Mode
14380	1376 / 617	No. 2 Bearing	Race Spin
14847	1547 / 893	No. 4 Bearing	Race Rub Cage
15696	1490 / 33	No. 4 Bearing	Cage Failure
16044	1917 / 361	Starter Seal	Worn
16257	2808 / 860	No. 1 Bearing	Race and Balls Scored
16441	1640 / 499	No. 2 Bearing and Housing	Scored
17108	1410 / 713	Fuel Control Drive Gear Spline Wear	Spline Wear
17423	1718 / 1325	No. 4 Bearing	Race Rubs Cage
17767	1480 / 546	No. 4 Bearing	Inner Race Rubs, Cage
21965	886 / 296	No. 2 Bearing No. 4 Bearing	Outer Race Fretting Plate Flaking
22763	1695 / 183	No. 4 Bearing	Failed

*TSN = Time Since New
**TSO = Time Since Overhaul

Chip Detectors

In order to determine the effectiveness of chip detectors, a review of R&M sample data was made, and the results are shown in Tables 16 and 17. Apparently the T55 chip detector has proven to be more effective than the T53 chip detector in indicating an internal engine problem. Both chip detectors were gearbox-mounted. The chip detector mounted in the T53 series engine installed in UH-1 series aircraft originally had the chip detector wired into the cockpit; however, this wiring was later disconnected and the mechanic must now periodically check the chip detector for continuity.

There are two types of chip detectors, the gearbox or open-pole, and the basket or full-flow. Both of these detectors have a central magnetic pole to attract magnetic particles, while the full-flow type has a screen that surrounds the pole and traps all particles in the oil line. Therefore, the full-flow type can detect the presence of conductive magnetic and nonmagnetic particles, while the open-pole only detects magnetic particles. The greatest problem with conventional chip detectors of this type is false alarms caused by "fuzz", and, for this reason, the pilot should not be alerted to a chip-detection alarm. When a bearing or gear produces chips as a result of surface spalling, the process is usually slow enough to wait until the end of the flight to detect. If, however, the chips are caused by cage failure, the damage rate is often too fast for the engine to be shut down in time. This condition also supports the argument for removing the chip detector interface from the pilot.

The false alarm "fuzz"" effect mentioned above can be reduced by a capacitive discharge burnoff chip detector being evaluated by the Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory. This development may make available a detector that could be useful for cockpit assessment of ferrous material oil contamination during flight. Basically it is a built in capacitor connected in parallel to a chip detector's contacts. When a voltage is applied through the indicator light, the capacitor becomes charged. As particles bridge the gap of the indicator terminals, the capacitor discharges. A small chip or "fuzz" is automatically burned off and the capacitor recharges. A large chip that does not burn off discharges the capacitor and provides a short that turns on the display light.

In general, we believe the chip detector to be a valuable maintenance and diagnostic tool. However, the performance of the chip warning indicator in the pilot's compartment has been erratic. Many cases of erroneous warnings of chip conditions have occurred, and the pilot, thinking the engine was failing, attempted an emergency landing that resulted in damage to the aircraft and crew injuries.

Table 16. Discrepancies Found as a Result of Chip Detector Activation

Period: T53-L-13 Sample - 15 June 1967 Through [illegible]ch 1969
T55-L-7/7B/7C Sample - 21 November 19[illegible] [illegible]ugh 31 March 1969

Engine Flying Time: T53-L-13 Sample - 94, 514 Hours
T55-L-7/7B/7C Sample - 89, 852 Hours

	T53-L-13 Sample		T55-L-7/7B/7C Sample	
Cause/Action Taken	Actual	Rate 10^6	Actual	Rate 10^6
Relevant Engine Failure	8	84	23	255
Cleaned and Reinstalled	35	370	12	130
Maintenance	3	31	1	11
Airframe	7	74	0	-
Unknown or Not Yet Determined	2	21	0	-
No Discrepancies Found	1	10	7	77
Total Number of Incidents	56	590	43	478

Table 17. Chip-Detector-Found Engine Failure Identified by Cause Component*

Cause Component	Number
T53-L-13 Sample	
Bearing, Number 4	1
Bearing, Number 21	2
Bearing, Number 45	2
Oil Impeller, Number 4	1
Faulty Detector	2
TOTAL	8
T55-L-7/7B/7C Sample	
Bearing, Number 1	2
Bearing, Number 6	2
Bearing, Number 7	1
Bearing Package Numbers 6 & 7	1
Bearing, Number 10	1
Bearing, Number 18	1
Bearing, Number 21	1
Bearing, Number 22	1
Bearing, Number 30	1
Bearing Package, Numbers 43 & 44	1
Sleeve, Number 2 Forward Seal	1
Torquemeter Drive Assembly	1
Cover, Accessory G/B	5
Oil Pump	1
Faulty Detector	3
TOTAL	23

*See Table 16 for additional data.

Perhaps a compromise can be made in which the chip detector wired into the pilot's compartment does not provide a continuous display, but which can be checked, on demand, by either pilot or maintenance personnel. This approach minimizes the risk of an unwarranted pilot action, yet makes the check available as an item on the preflight check-list.

Turbine Engine Parameter Sensors, Monitors, and Fault-Warning Devices - General

Some of the many methods used today to obtain data on engine condition are the advanced techniques of AIDAPS* and AIDS** and simple visual and aural methods. Most of these methods are used for engine condition monitoring interface with the maintenance organization, since the failure mode detected is usually a gradual process, which allows some time in which to schedule corrective maintenance actions. The above methods are not discussed in this report since they are well documented in manufacturer's handbooks, manuals, etc.; however, some methods of condition monitoring used by Lycoming will be described.

Borescopes are extremely useful for viewing the internal structure of the engine. There are two basic types, the rigid and the flexible. They both operate on the principle of having a noncoherent fiber bundle, which carries illumination to the viewing tip area, and a coherent fiber bundle that extends from the viewing tip to the eye piece. The rigid borescope is useful for inspecting compressor blades, because after removing stator bolts, the borescope permits a directline view. Handling of the rigid borescope is fairly simple. The flexible borescope is much more difficult to use, since the tip is articulated by means of an external handle, and the operation is performed "blind". For this reason Avco Lycoming has developed guide tubes for the combustion chamber so that the borescope can be guided to the area to be viewed; i.e., the fuel nozzles, swirl cups, liner, and first-stage gas generator turbine nozzle.

Another useful tool, developed by Lycoming, is the compressor performance monitor. This tool comprises a system that provides a readout of referred*** compressor speed. During engine testing, this tool is connected to engine sensors to obtain readouts of:

---

*AIDAPS - Automatic Inspection Diagnostic and Prognostic System
**AIDS - Aircraft Integrated Data System
***Speed corrected for ambient temperature

a. Compressor speed.

b. Compressor inlet pressure.

c. Compressor exit pressure.

d. Compressor inlet air temperature.

The engine is accelerated slowly until it reaches a preselected compressor ratio. At this ratio, the system shows the referred compressor speed which is then compared with the baseline speed. As the compressor becomes dirty or eroded, its speed must be increased to maintain the same pumping capacity; i. e., pressure ratio. If the compressor is dirty, cleaning it will restore the pressure ratio/referred speed balance. Cleaning will not help if the compressor is eroded. Consequently, the compressor will require restoration or replacement if the speed increases to the operating limit.

Parameter monitoring and interrogation, either on or off line, is intended to give the pilot and/or crew chief timely warning of engine failure or damage.

The types of engine failures or damage that are typically monitored for pilot warning are those that affect safety-of-flight. However, the crew chief also requires data that provides early detection of engine failures that would affect mission reliability or aircraft availability.

Safety-of-Flight

Most engine failures that affect a mission or the safety of the aircraft occur abruptly, with little or no warning of impending danger, and can sometimes be catastrophic. Very little can be done to monitor random failures due to bad workmanship, material deficiencies, battle damage, etc. The best solution to preclude these types of failures is to improve reliability of the basic engine. There are however, repeatable failures that give no warning but can be monitored. These are caused by low-cycle fatigue (LCF) and stress rupture (creep). Low-cycle fatigue is damage caused by cyclic variation of strain, from which damage can culminate in an abrupt, catastrophic failure of a disc. Creep is a process of slow deformation of solid materials over extended periods of time while subjected to high loads and temperatures. This damage causes blade elongation, leading to rubs. These phenomena are usually monitored through bookkeeping of flight profile data; but because of the inherent inaccuracy of such methods, they are rated very conservatively. The engine usage indicator[4] (EUI) developed to provide exact data on LCF and creep continuously monitors engine gas temperature and rotor speed. These data are then automatically processed to provide odometer readouts, which provide hard values that are used to retire components. These values are strictly dependent on usage of the engine and are not time-based.

One system that is unique to Lycoming is the bearing wear-trace program. The silver plating of the bearing cage retainer is interrupted at a critical wear depth, and a thin layer of an isotope of silver is deposited. The normal silver plating is then resumed to the full depth.

As the cage wears normally, silver is released into the oil until the wear reaches the isotope layer. Then the silver isotope is released and is detected by a Geiger Mueller counter that is either permanently mounted in the lubrication system or used periodically as a dip stick in the oil tank.

Other types of available oil monitors use optical and radiographic techniques; but these monitors are relatively new devices, and insufficient data are available to determine the long-range benefits gained by their use.

COMPARISON OF DEPOT RETURNS - ALL CAUSES FOR DIFFERENT ENGINE APPLICATIONS.

Military Peacetime Operation Versus Military Wartime Operations

To evaluate the impact of wartime operations on engine returns to depot, a study of the T53-L-11A/11B engine returns from Vietnam versus other military locations was made (refer to Table 18). It should be noted that, for the most part, these engines were not equipped with particle separators or FOD screens. As expected, there was a large increase in returns (5 times greater) due to environmental causes during wartime operations. Returns resulting from operations and maintenance error increased 2.3 times over that of peace-time operations, while the number of engines reaching TBO was reduced by a factor of 2.5 times. Engine returns attributed to engine causes (component) were similarly affected and increased by about 2.5 times that of peacetime operations.

It appears then that engine returns to depot, other than from environmental causes, increase about 2.5 times when a military aviation unit goes from a peacetime to a wartime operation and, accordingly, the number of engines reaching TBO decrease by a similar amount.

---

4 R. Hohenberg, The Engine Usage Indicator, An Instrument to Assess the Expenditure of Useful Gas Turbine Life, Fourteenth International Gas Turbine Conference, Cleveland, Ohio, March 1969.

Table 18. T53-L-11A/11B Engine Returns - Vietnam Versus Other Locations[2]
(1 January 1967 Through 30 June 1968)

Cause of Removal to Depot	Vietnam Flying Hours, 1,914,770			Other Than Vietnam Flying Hours, 566,452		
	Number of Depot Returns	Return Rate 10^6 Hours	% of Total Analyzed Returns	Number of Depot Returns	Return Rate 10^6 Hours	% of Total Analyzed Returns
Environment	1,902	993	63.2	107	189	33.8
Sand and Dust Erosion	892	466	29.6	33	58	10.4
Foreign Object Damage	980	512	32.6	70	124	22.1
Inlet Blockage	12	6	.4	4	7	1.3
Other Environment	18	9	.6	0	0	0.0
Operating, Maintenance and Airframe Causes	165	86	5.5	21	37	6.6
Operator Error	15	7.8	0.5	3	5.3	0.9
Maintenance Error	80	42	2.7	13	23	4.1
Airframe Causes	70	37	2.3	5	8.8	1.6
Handling Damage	11	5.7	0.4	3	5.3	0.9
Inspection/Calibration	1	.5	0.0	0	0	
Maximum Time Achieved	127	66	4.2	96	169	30.3
Combat Damage	89	46	3.0	0	0	0
Unconfirmable/No Problem	251	131	8.3	37	65	11.7
Engine Caused	464	242	15.4	53	94	16.7
Total	3,010		100.0	317		100.0

Since military engines are now usually equipped with particle separators and FOD screens, we believe that the 2.5 factor will also apply to environmental causes, if engines are redeployed in combat roles.

Commercial Returns Versus Military Engine Returns

A comparison of commercial returns and military returns was made to determine the areas in which they were different and the causes for these differences.

The commercial composite TBO-achieved rate for the engines studies is 139 per million hours which, in terms of flying hours, is slightly less than 144 per million for the best military engines (T53-L-11 Series). However, for much of the period studied, the military schedule TBO was set at 1,200 hours, while the commercial model was 2,000 hours. Therefore more commercial engines were reaching the military TBO than is apparent from the data. As seen in Figure 7, more than 25 percent of the commercial engines are returned due to TBO limitations, while less than 6 percent of the military engines reach TBO (see Figure 6). This is of course, due in part to the high number of military premature returns resulting from environmental causes. To get a better understanding of some of the basic differences between commercial and military operations, the records of one commercial operation were selected after tracking the data for over 67,000 flying hours, and the following comparisons were made:

a. The depot return rate for all causes on commercial T5313B engines was 504 per million hours, while the 1973 Military T53-L-13B engine was 1221 per million (almost 2.5 times greater).

b. The depot return rate for unscheduled engine causes was 67 per million hours for commercial engines, while the military rate was 301 per million (about 4.5 times greater).

c. By chance, the commercial operator had also flown over 7,000 hours in Saudi Arabia. This desert operation consisted of flying in a combination of salt and sand environments. In this operation, engine-caused returns were almost double that of this same operator's Continental U.S. operation. So there appears to be a correlation between engine-caused (components) returns and the environment. Even though the commercial operator moved to a hostile environment and his engine-caused return rate went up, it was still less than one-half that of the peacetime military engine-caused return rate.

A significant factor in engine deterioration is the mission profile, including start cycles per hour. A comparison of the commercial operator's duty cycle, and the duty of the AH-1G is shown below.

	Military[5]	Civil
Flying Hours per day (Utilization)	1.85	3.75 hours
Duration of each flight	30 minutes	1 hour
Cycles per hour	3 to 6 (estimated)	1

Since several of the rotating components on the commercial engine are low-cycle fatigue limited, the commercial operator is much more concerned with minimizing cycle accruals. For example, he may elect to leave the engine running at intermediate stops to avoid accumulating temperature cycles. He is also aware that cycles represent money because of hot-end component deterioration and, therefore, makes an effort to minimize maintenance costs.

The Avco Lycoming experience in dealing with commercial helicopter operators has shown that they are very cost conscious and will do all they can to retain an engine in the field. To be competitive, they must minimize expenses, including spare-engine and spare-parts inventories. A commercial operator tends to rely upon the manufacturer for the more expensive spares, while keeping on hand for his own use a small supply of high-usage items such as igniter plugs, start fuel nozzles, O-ring seals, and other small hardware.

If a commercial operator feels that a necessary repair is beyond the capability of his mechanics, he often requests the services of the manufacturer's technical representative rather than return an engine for minor repair or overhaul. Should an oil-contamination or a chip-warning indication be experienced, the civil operator, in most cases, will make a conscientious effort to find the item at fault and, if field repairable, will return the engine to service after suitable cleaning and inspection, whereas, the military will often remove an engine and return it to depot after a cursory check.

---

[5] Management Summary Report AH-1G, Technical Report 72-28, U.S. Army Aviation Systems Command, St. Louis, Missouri, July 1972.

On the average, the civil operator has more experienced maintenance personnel, many of whom received their initial training and experience in the military.

Although it is written to a different specification and format, the commercial maintenance manual contains essentially the same data as the military manual. The scope of the commerical versus the military maintenance manual is not considered as a significant factor in the difference in ability to perform field maintenance.

Similarly, the military has the advantage when it comes to the types, quantities, and availability of special tools, including diagnostics equipment.

With the preceding factors being somewhat balanced, it is probably the stronger need to be economically competitive which drives the commercial operator to perform engine maintenance at the lowest possible repair level.

Established TBO and Inspection Periods

In both the military and commercial applications, time-between-overhaul interval determinations are based, to a large degree, on the operating experience accumulated on previous models of similar configuration. Where that experience is not applicable because of a completely new design, then the interval is usually two-to-four times that of the 150-hour qualification test. In the case of the T53-L-13, the initial TBO was set at 600 hours after a 150-hour qualification program. The TBO interval on T53-L-13Bs now based at Ft. Rucker has increased to 2, 400 hours.

In some cases, the TBO interval for a particular engine model may be limited because of a specific component problem. For example, the T53-L-13A was issued an initial TBO interval of 1, 200 hours because of its commonality with the T53-L-11B, its predecessor, which had a 1, 200-hour TBO at that time. However, when the compressor disc problem developed, the TBO was reduced to 600 hours. After incorporating the titanium rotor, the TBO was returned to 1, 200 hours.

Currently, the engines operating in the test program at Ft. Rucker are accumulating hours far in advance of those at other operating sites. Periodically, these engines are disassembled and inspected either at Ft. Rucker or at a contractor's plant where dimensional, magnaflux, and fluorescent-penetrant inspections are performed and the data recorded.

These data are retained for the next inspection to provide a basis for development of field and overhaul inspection criteria. If warranted, a recommendation is made to increase the TBO interval.

The procedures established to determine the TBO interval for commercial operations are conducted under the jurisdiction of the Federal Aviation Administration and, while differing in detail, are much like those for the military. The initial interval is based on the degree of commonality with a known model. If the engine is a new design or incorporates major changes over its predecessor, then the initial interval is based on the manufacturer's component and engine test data. Since FAA test requirements are quite severe and more demanding than those that a typical operator is likely to incur, the initial TBO is usually set from two-to-four times that of the 150-hour qualification test. Like the military, the operator with the high-time engines is often encouraged to participate in a TBO extension program.

The TBO program consists of a series of inspections to assure the integrity of the engine as higher time is accumulated. As warranted, the TBO interval is increased for all operators. Figure 43 graphically shows the increase in TBO and TBI (time between hot-end inspections) for the commercial T53 series engines during a 10-year period.

UNSCHEDULED UNNECESSARY RETURNS - DEFECT NOT SUBSTANTIATED

This category represents a significant number of depot returns, 121 per million hours in the composite and 661 in real numbers (refer to Table 19). When this category of engines was returned for overhaul, it was usually determined that the returns were not only unnecessary but that the defects for which they were returned were not the actual problems. Although in some cases no defects could be found, some field-repairable problems were found in others.

If we consider the reason for return as a symptom, then problems like high exhaust gas temperature, low power, hot starts, vibration, and high or low oil pressure are common to the selected engines studied. It can be assumed then that combinations of troubleshooting procedures, diagnostics equipment, or personnel training related to these return events were not adequate. Consequently, because of the large number of engines returned to depot, it is recommended that further study be initiated to investigate maintenance and diagnostics equipment and procedures.

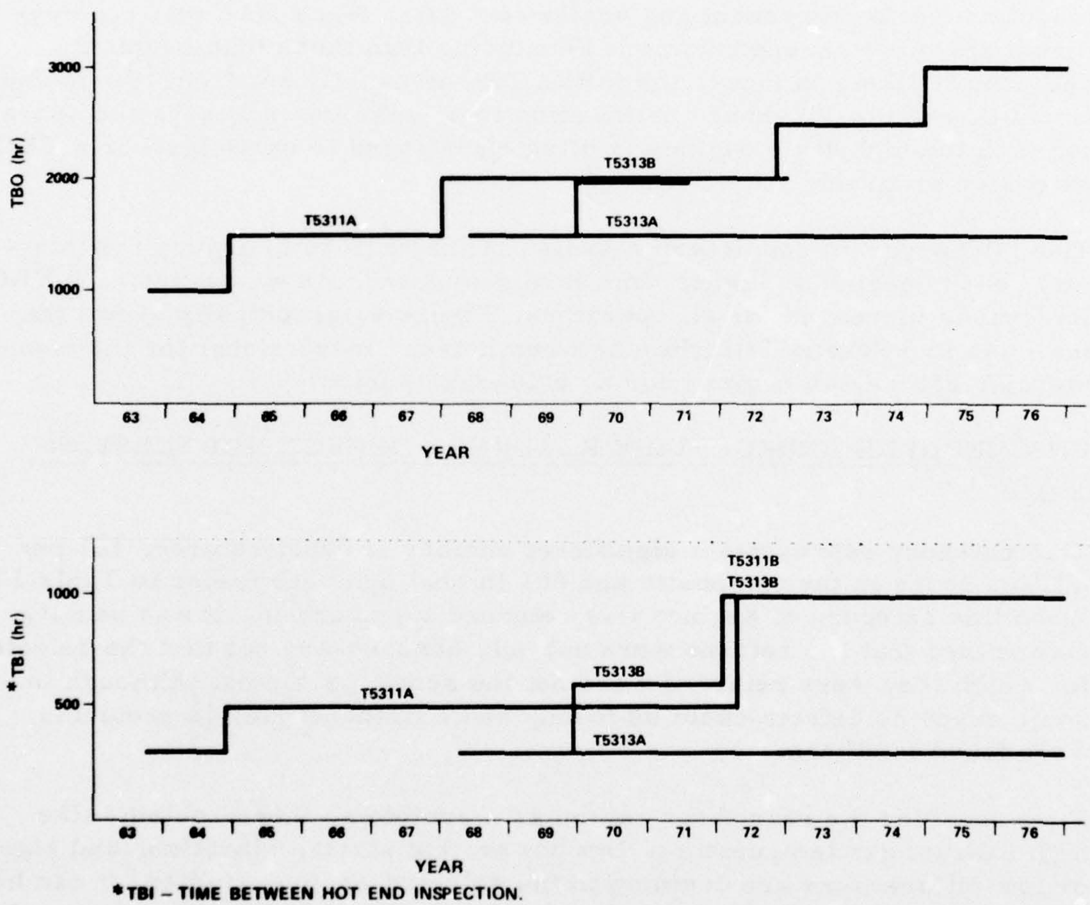


Figure 43. TBO Growth of T53 Commercial Engines (Rotary Wing Applications)

Table 19. Engine Returns - Defects Not Substantiated

Engine Model	Number	Percentage	Rate (Per Million Hours)	Operating Hours
T53-L-11/11B	146	5.6	117	1,250,000
T55-L-7/7B-C	60	7.1	117	512,406
T53-L-13A	354	9.2	208	1,700,000
T53-L-13B	86	8.1	99	869,291
Commercial	15	2.4	13	1,136,911
Total	661	7.3	121	5,468,608

UNSCHEDULED, CONVENIENCE RETURNS

Unscheduled, convenience returns are those engines that could have been repaired in the field but were returned to depot. This type of return has been categorized into engine-caused and environmental-caused.

Analysis of the T53-L-13A/B data revealed that the convenience return rate for seals was greater than any other component. As previously discussed, the replacement of Number 2 bearing seals is a time-consuming procedure that requires the removal of the hot section, two gas producer turbines, and two gas producer nozzles. It is understandable why field-maintenance personnel might be reluctant to expend man-power replacing these seals, particularly if an adequate number of spare engines are available or if the engine had evidence of other defects, such as erosion that might necessitate its return in the near future.

The difficulty associated with isolating the cause of oil contamination constitutes another group of convenience returns. Assume a bearing is generating enough metal fuzz to activate the chip detector, the procedure outlined in the maintenance manual requires removal of several scavenge lines to determine the presence of metal. If the results are negative, the field mechanic then finds it difficult to localize the source. Chances are, he will send the engine to overhaul rather than disassemble various sections looking for the bad bearing.

Environment-caused returns such as FOD and combat damage are other cases where considerable effort is usually required to return the engine to service. In the case of FOD, the upper compressor case half is removed, damage blades or stators are replaced if necessary, the case is reinstalled, and then an engine vibration check must be performed. The distribution between engine causes and environmental causes of unscheduled convenience returns is about 50/50 (see Tables A-1 through A5) and may reflect the degree of repair difficulty as much as anything else.

Under the Army aviation maintenance concept, an organizational unit will send to the next higher level, direct support or general support, any engine that is beyond its authorized repair capability. If the receiving units' workload is high, rather than stockpile these unserviceables, they may elect to send them on to depot, particularly if these engines involve high-repair risk, or excessive man-power to repair.

Unfortunately, while we recognize the reasons for most of these returns, it remains that approximately 17 percent of the engines that were returned for overhaul could have been repaired at lower levels. If we assume a repair/overhaul cost of $14, 871,[5] neglecting transportation and what it *might cost to* do the repair at field level, this represents an expenditure of funds in the order of 100 million dollars.

2.0 CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Based on the results of this effort it is concluded that:

1. The rank order for engine depot return causes (see Figure 2) is:

a.	Environment/System	42.22%
b.	Engine - Component	18.39%
c.	Convenience	17.71%
d.	Unnecessary	7.34%
e.	Scheduled	6.48%
f.	Reason Unknown	4.03%
g.	Conversion	3.61%
h.	Service Bulletin Modification	.22%

   Environment/system caused returns have exceeded engine-component caused returns by a factor greater than two.

2. The two largest causes of environmental/system caused returns were (see Figure 11):

a.	FOD	50.78%
b.	Erosion	20.42%

   This has been attributed to lack of protection screens and separators in hostile environments.

3. Engine - component caused returns were second in rank order. The leading components causing engine depot returns were (see Figure 18):

a.	Mainshaft seals	37.62%
b.	Bearings	25.85%

4. The component/failures causing depot returns and impacting flight safety or mission reliability were (see Table 3):

   a. Rotating components

      (1) Discs

      (2) Blades

      (3) Bearing cages.

5. An average of 29 percent of engine-caused returns to depot were for oil contamination by metallic particles. In most cases it was not apparent in the field, what caused the contamination or if field maintenance could have been performed to correct the problem (see Figure 40).

6. Convenience returns were the third largest category of the composite engine returns. While these returns may have been due mainly to pressing tactical and logistic situations some of them may have been due to the difficulty of repairing in the field.

7. Although the chip detection system has proven to be a valuable diagnostic tool in monitoring bearing and gear condition, it is believed the chip indicator is useful mainly as a maintenance indicator and is of limited value as a pilot warning device. The more common or frequent failure modes of wear, spalling and race rotation generate metal in the oil at a slow and uniform rate, which can be monitored at daily or preflight inspection periods. The less frequent failure modes of fracture involving gear tooth or bearing cage, may result in rapid engine power loss, affording no advanced warning advantage.

8. An average of 7.34 percent of the total engines returned to depot for overhaul were returned for reasons or symptoms which could not be substantiated (see Figure 2).

9. The TBO evaluation and analysis indicates high initial TBO or on-condition overhaul programs are feasible. However, the data in Part I show only 6.5 percent of all engine (composite) returned to depot were because of achievement of maximum time, and the larger drivers of overhaul returns are associated with unscheduled causes. For example assuming a 15,000 dollar average overhaul cost with a total operating time of 27 million hours, the overhaul costs for

maximum time engine overhaul was 43.3 million dollars, but the overhaul cost for all the unscheduled returns totalled 623.7 million dollars. This is highlighted to emphasize that greater economic gains can be realized by first addressing a reduction in unscheduled depot returns.

RECOMMENDATIONS

Based on the conclusions of this report, it is recommended that:

1. Further effort to reduce the engine depot overhaul events or costs should address the total airframe operational system use.

2. The engine specification must adequately describe the environment in which the engine will be used. The engine design should allow for the optional installation of particle separators when required. FOD screens should be permanently installed with facilities for cleaning and servicing.

3. Reduction in the engine-component caused category can be approached by two methods. First, component design must be optimized for maximum service lives and reliability. This is especially important where the subject components cannot be field repaired or replaced and cause the engine to be depot returned. Components in this category should be designed with wear lives in excess of 5,000 hours. Second, the engine design from the assembly viewpoint must consider ease of accessibility for field replaceable components having wear out failure modes requiring frequent replacement. The engine design should allow for these components to be replaced in the field without complicated axial tolerance computations or shim adjustments.

4. The design approach to components having failure modes impacting safety and mission as well as depot return, must be treated with extreme conservatism. An example is the discs in the compressor and turbine sections. Conservative estimate of the material strengths should be employed by selecting the lower two (2) sigma value for yield, and the lower three (3) sigma value for fatigue strengths. Design values for these component failure modes should be verified by component testing (see Testing Recommendations). A recommended method for the reliability analysis of rotating components is the stress-strength interference method which is described in Appendix F. The method or model for combining component probabilities to meet a specified engine time interval-probability is described in subsequent paragraphs.

5. Consideration should be made in lubrication system design to isolate the main bearing scavenge tubes for purposes of chip source detection and containment. Such systems would allow improved bearing condition monitoring, and increased field maintenance capability with consequent depot and overhaul avoidance.

6. Improvement in field repairability through engine design be made to help reduce the frequency of convenience returns. As outlined previously, these design improvements should result in less complicated maintenance procedures which can be accomplished with a greater degree of confidence.

7. The chip detector monitor system should not provide a continuous cockpit display. A "demand" check which can be made by the pilot or maintenance personnel, would minimize unwarranted emergency procedures caused by "fuzz." The capacitor discharge chip detector discussed in the text would accomplish this automatically.

8. Further studies be made to determine the cost effectiveness of improved diagnostic systems in reducing unnecessary engine returns to depot. However these studies are not a prerequisite for on-condition maintenance programs.

TESTING RECOMMENDATIONS

The use of a high initial TBO must be substantiated by component and engine testing experience. Initial design verification and qualification of engine and components are adequately covered in MIL-E-8593A. However, this specification does not adequately cover the type and extent of testing necessary to assure the achievement of a TBO interval. Therefore, additional engine and component testing over that required by MIL-E-8593A is recommended to help assure achievement of a particular TBO interval.

BEARING AND SEAL COMPONENT RIG TESTS

Because of the relatively high depot return rates due to bearings and seals, extended service life rig testing is recommended. The rig tests should simulate the conditions of load and environment found in actual engine operation for specified mission profiles. It is recommended that the total testing on each component be at least two times the specified TBO interval. The wear lives determined in these tests will be used to substantiate the specified TBO interval and will be useful in evaluating future engine TBO extensions.

ENGINE TESTING

Endurance Testing

Although endurance testing performed in accordance with MIL-E-8593A, paragraph 4.6.1, is performed to qualify an engine, results of this test have been related to initial TBO intervals. The engine endurance duty cycle in this test is more severe than most cycles including that associated with the UH-1H. The required power operating points allow for twenty-five 6-hour cycles with worst-case turbine inlet temperatures. The adverse effects on static hot-end components (shortened life periods) should not impact the TBO interval since these parts are designed for field maintenance. The effect on rotating parts, turbine discs, blades, and bearings (shortened life periods) would impact the TBO interval since their secondary failure effects can cause depot returns. The front end of the engine (bearings, seals, compressor blades and discs) would also be subjected to higher temperatures, although the increased temperature in this section would not accelerate part wear-out to the same degree. However, compressor discs and blades having fatigue failure modes experience accelerated failure stresses from the frequently exercised (every eight minutes) torque runs (paragraph 4.6.1.3b, MIL-E-8593A). The primary value of endurance testing in the establishment of high initial TBO is the ability to expose incipient component failure modes which could impact mission reliability or flight safety. Because of the severity of these tests they are usually restricted in time to 150 to 300 hours. More recently factors up to 6 times the endurance test hours have been used to establish an initial overhaul interval time.

Mission Duty Cycle Testing

This type of testing to the actual mission duty cycle is divided between test cell and airframe. Because of the possibility of engine-airframe interaction, the greatest portion of operating testing time should be conducted on the airframe. The engines should be instrumented for initial airframe testing and the readings compared to test cell baseline data. Significant differences caused by airframe interactions must be eliminated before additional testing is started. If test data verifies that there is no significant differences in cell and airframe testing, these test hours can be combined. On this basis, one hour of cell testing would equal one hour of airframe testing. In the new engine programs, a minimum mission duty cycle testing time of two initial TBO intervals should be planned. With this minimum schedule, two engines are used, one for test cell and one for airframe testing. Periodic inspections, and inspections made after the completion of the tests, are made on each component containing failure modes which can cause depot returns. Successful completion of the testing is reached when these components demonstrate their capability of operating for one or more multiples of the TBO interval that is being considered to be imposed on that engine.

Low-Cycle Fatigue

Low-cycle fatigue (LCF) tests can be designed to compress many fatigue cycles into a short time frame. As an example, if the mission contained two cycles per engine operating hour, and the LCF test plan called for ten equivalent cycles per test hour, a time factor of five can be established. This type of testing can also be designed to approximate total time at mission power levels. It is important to include adequate running time at low power levels where component failure modes such as bearing skidding and race rotation may be caused by light or partial loads. The testing period for new engines being used to verify the initial TBO interval should be at least one life cycle. Periodic inspections should be made to determine the deterioration of individual components. Wear or crack propagation rates noted during inspection periods can be used to establish field repair limits and component wear lives. The component data derived from these tests should be used to verify and improve the original component design life estimate. Low-cycle fatigue testing should be run per AV-E-8593 paragraph 4.5.9 for a minimum of 3,000 cycles. However, if the engine contains components whose recommended retirement time/cycles exceed 3,000 cycles, the test should be run to include the higher number of cycles.

A graphic representation of the various types of tests and their expected relationship to the TBO interval is shown in Figure 44. A rule of thumb in commercial aviation has been to allow up to five times successfully passed qualification endurance testing hours for initial TBO hours. The rationale for this factor has never been truly established. However, its use has resulted in the establishment of initial TBO's as high as 1,200 hours. This upper time limit in related TBO hours is because the endurance testing recommendation in MIL-E-8593A is for 300 hours (two 150-hour phases).

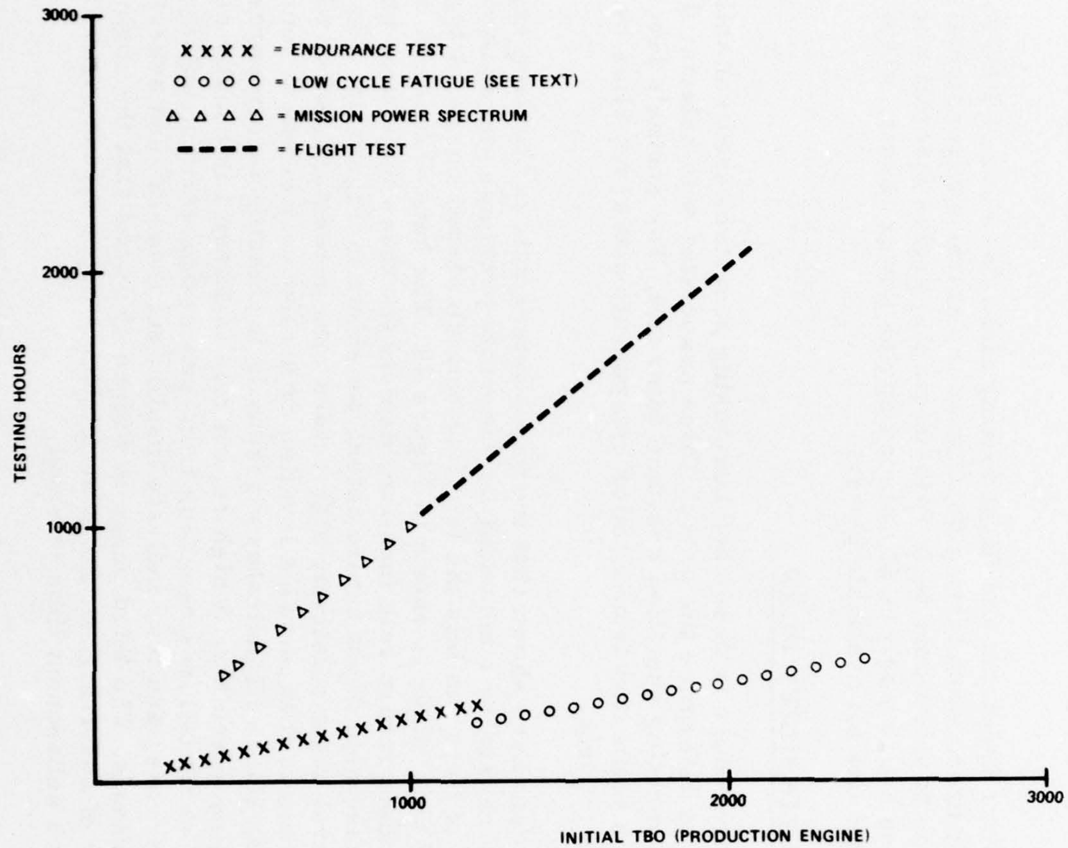


Figure 44. Initial TBO (Production Engine) Versus Test Hours

The relationship of low-cycle fatigue and endurance testing time to initial TBO hours shown on Figure 44 is the result of a five-to-one ratio as explained in the preceding paragraphs. The equating of cycles to time for turbine engine durability estimates is valid since fatigue is the principal failure and life limiting mode for those components causing depot returns.

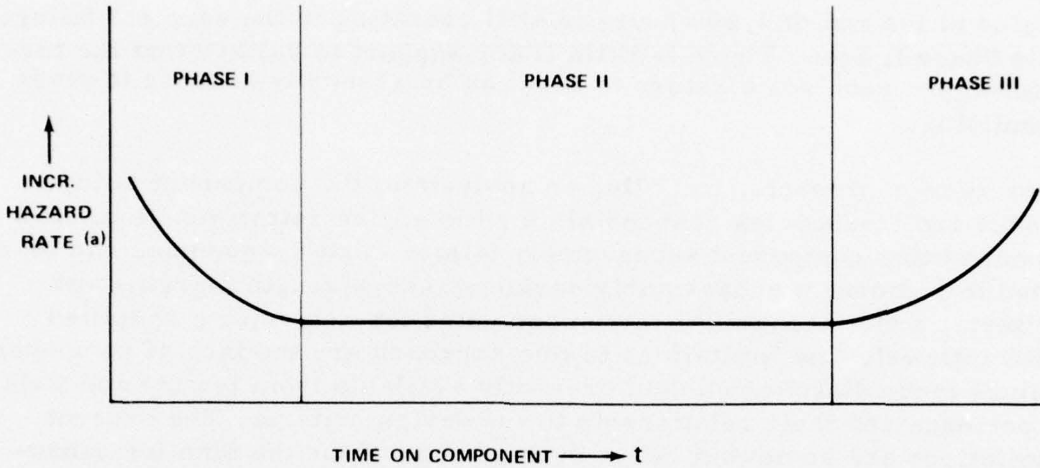
Mission power spectrum and flight testing allow one hour of TBO for one hour of test time, when testing duplicates the actual environmental use. An exception to this would be in twin-(multiple) engine aircraft where flight testing hours would be at reduced engine power levels, while cell testing might use all available power.

DESIGN RELIABILITY PLAN

A plan or procedure is described here using preestablished reliability techniques to determine the probabilities associated with selected design margins in meeting specified overhaul intervals. The engine's level of capability is estimated from subtier components and assemblies by the use of math models.

Historical data have shown that the depot return rate for turbine engine assemblies caused by component or assembly problems and analyzed as a function of time exhibits the familiar bathtub shaped curve. A typical example of this curve is shown in Figure 45. The hazard function or time-dependent return rate function, depicts the three main time phases of engine assembly depot return rates. As shown in Figure 45, Phase I (at low hours) has a relatively high return rate percentage, after which the second phase then shows a leveling or a relatively constant return-rate period. Phase III indicates a gradually increasing return percentage for the engine assembly. A high return rate in Phase I is usually an indication of early failures resulting from processing errors, quality, and assembly errors, and may indicate insufficient "run-in" and acceptance testing intervals. The third phase in Figure 45 shows that the engine's probability of surviving, or not precipitating a depot return event dimishes with each subsequent time interval.

Nonparametric analysis of engine depot return rates will vary for different engine models and deployment periods. Figure 46, which is a plot of the actuarial table in Appendix B, shows the percentage of return to depot for engine component causes during an 1,800-hour period for the T53-L-13B. The smoothed curve for engine component causes shows a fairly constant return percentage as a function of time over the 1,800 hour operating age. Related to the bathtub curve this indicates that the



(a) THIS IS THE INSTANTANEOUS FAILURE RATE OF A COMPONENT AT ANY TIME; GIVEN THAT IT HAS BEEN OPERATED UP TO THAT TIME.

Figure 45. The Bathtub Curve

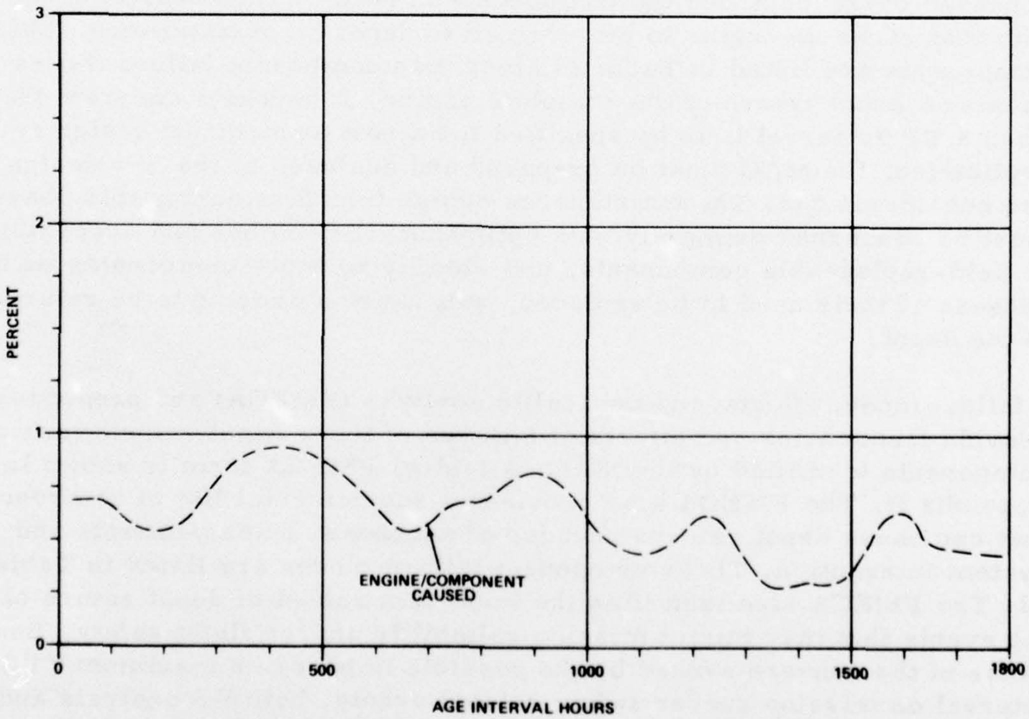


Figure 46. Percentage of Engines Returned to Depot Due to Age - T53-L-13B

engine at the end of 1,800 hours is still operating in the constant failure rate Phase II area. There is little if any support to believe that the turbine engine requires a return to depot as an assembly because it needs rebuilding.

This section presents, initially, an analysis of the component failure modes and frequencies responsible for the engine return function. It is assumed that component subassembly failure mode frequencies can be related to component subassembly design stress/strength margins and criteria, and a probability can be computed for achieving a specified TBO interval. The limitations to this approach are the lack of component failure mode distribution data presently available from testing and field experience and their relationship to the design criteria. The present limitations are somewhat offset in that reuse of the the plan for subsequent designs and redesigns will ultimately produce improved and refined component backup data. The reliability support interfaces and data feedback flow supporting the plan through the initial design, development test, and operational phase are outlined in Figure 47. The relevant component data list which is to be analyzed for failure mode impact on depot returns is derived from the Maintenance Allocation Chart (MAC), an example of which is included as Appendix C. Assuming independence of events, this appended chart identifies the components in need of replacement or repair that cause an engine to be returned to depot for maintenance. These components are listed in Table 20 along with component failure modes causing a depot return of the complete engine. It becomes apparent that when a TBO interval is to be specified for a new or modified design or application, the MAC must be prepared and analyzed to the new design use considerations. The maintenance design interface during this phase must be concerned primarily with optimizing the number and accessibility of field-replaceable components, and identifying those components which, because of their need to be replaced, will cause an engine to be returned to the depot.

A failure mode, effects, and criticality analysis (FMECA) and prediction provide frequencies and effects of failures of those depot return-causing components identified by the MAC. A typical FMECA form is shown in Appendix D. The FMECA also provides a supplemental list of components that can cause depot returns because of secondary damage effects and system interaction. These component failure modes are listed in Table 21. The FMECA also identifies the important subset of depot return causing events that may impact mission reliability and/or flight safety. Because of the concern evoked by the possible impact of a maximum TBO interval on mission and/or safety related events, both the analysis and design requirements of this group are treated independently (See Figure 48).

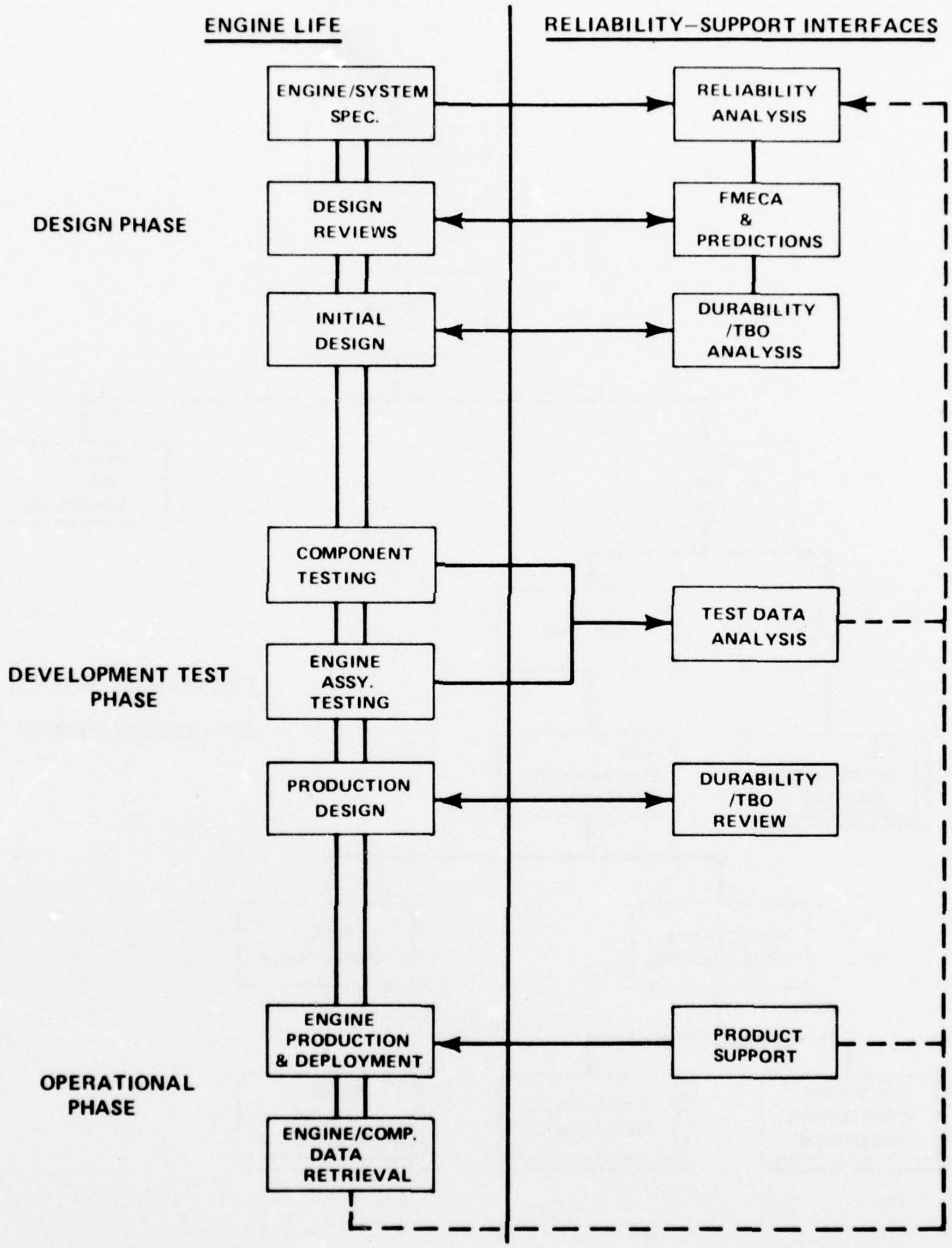


Figure 47. Data Feedback System Flow Diagram

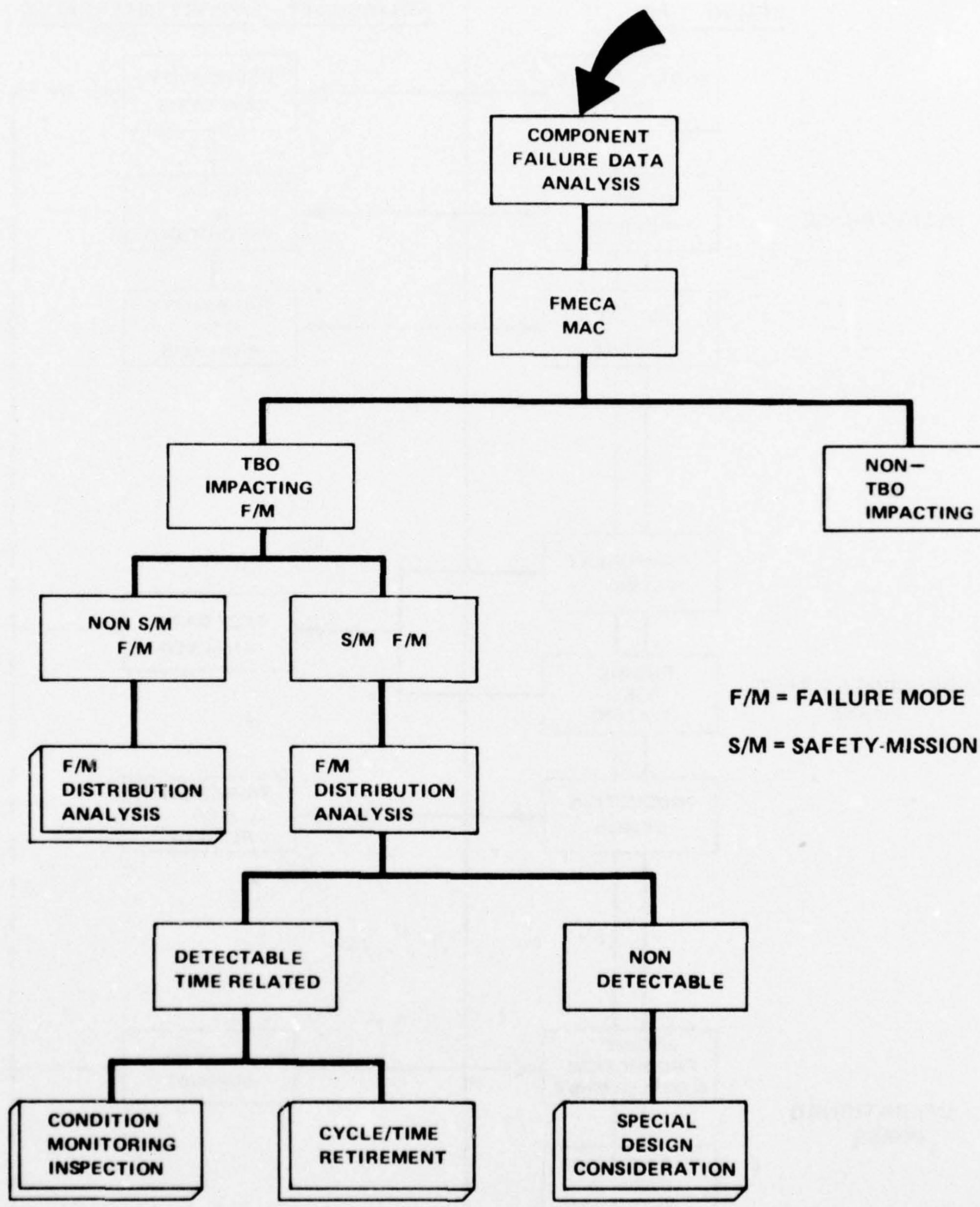


Figure 48. Failure Data Analysis Flow Path

It is recommended that TBO-interval requirements, as part of the engine specification, include a probability level. For example, a typical requirement that will be used to explain the following text might state the achievement of a 2,000-hour TBO with a 90-percent probability and a 5,000-hour TBO interval for those events impacting the aircraft mission or safety at a 99-percent probability. Because the design and development phase is specifically concerned with the ability of the engine and its components to operate satisfactorily within the specified environment and duty cycle, the TBO design analysis is limited to events that are engine-component caused. In addition to a complete set of performance requirements, the system specification should include a proposed engine duty cycle and an adequate description of the type of deployment and environmental stresses to which the aircraft and engine will be subjected.

EXAMPLE OF DESIGN RELIABILITY ANALYSIS

The example which follows is used to show how the steps outlined in Figure 49 may be used to "design in" specified TBO intervals. For purposes of clarity, the example relationships selected are simplier than those which would normally be encountered, but this does not limit the validity of the method.

The specification for the example engine requires an initial TBO interval of 2,000 hours with a 90 percent probability of achievement. In addition there is a requirement for a 5,000-hour interval which will not incur a depot return which would also impact mission reliability or flight safety. There is a 99 percent probability of achievement required for this interval. The engine is to be used in a single-engine helicopter troop transport application operating in remote positions from unimproved pads with heavy exposure to sand, dust, and FOD conditions. The engine duty cycle for this mission is shown in Figure 50.

The data analyzed in Section 1.0 showed that environmental causes were the primary reason for unscheduled engine depot returns. The installation of FOD screens and particle separators on T53 engines was largely instrumental in reducing depot return rates by the factors 6 and 10 respectively (see page 36). There is little doubt that the initial configuration design application should include environmental protection. Tradeoff studies may be necessary to ensure that other performance requirements can still be achieved. Concurrent with these analyses would be the optimization of the compressor design for operation in hostile environments. The design for surge margin and compressor components, such as blades, vane supports, inlet guide vanes, and bleed systems must be adequate for operation in unclean and erosive atmospheres. Material

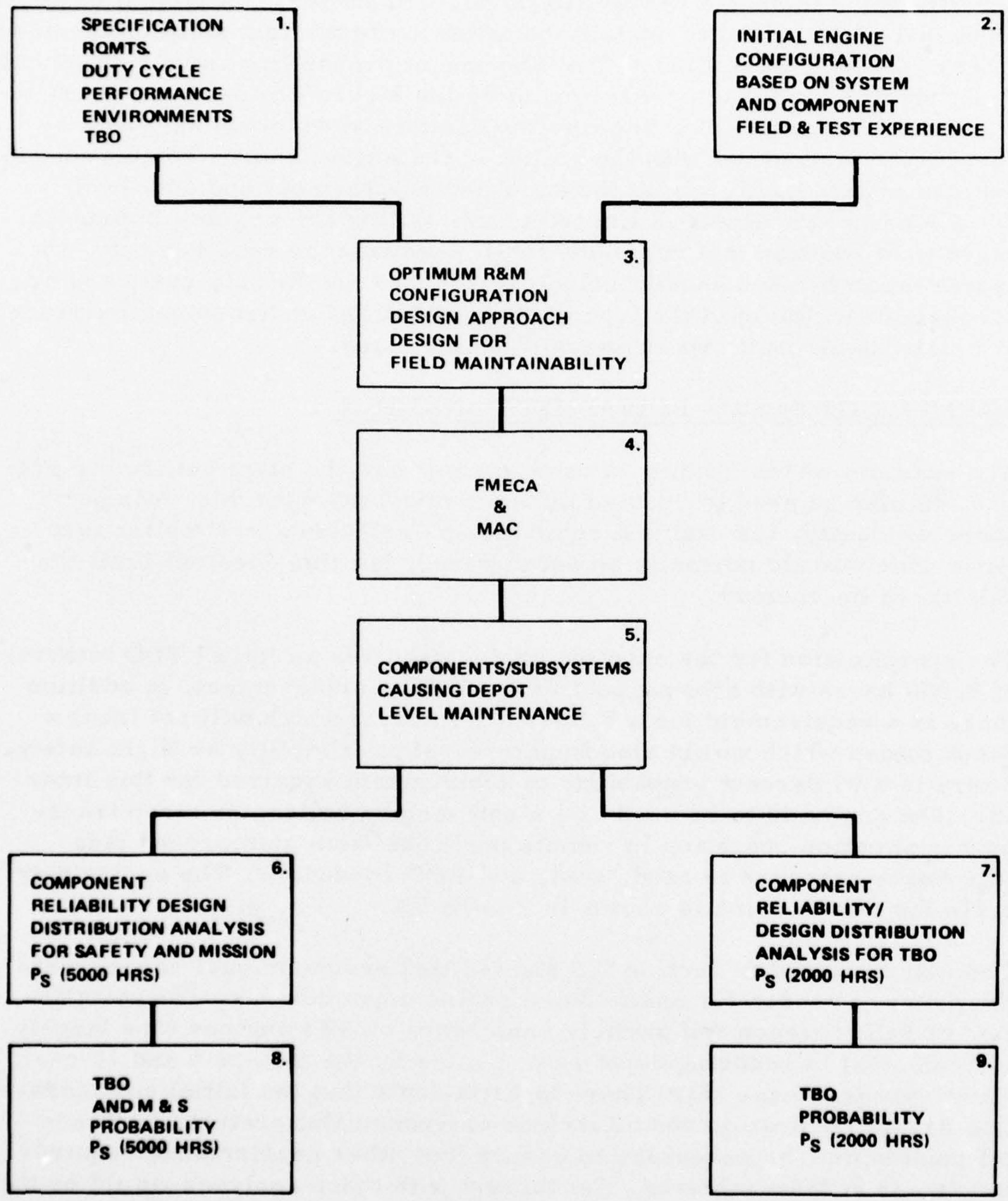


Figure 49. Analysis Flow Path for TBO Interval Design

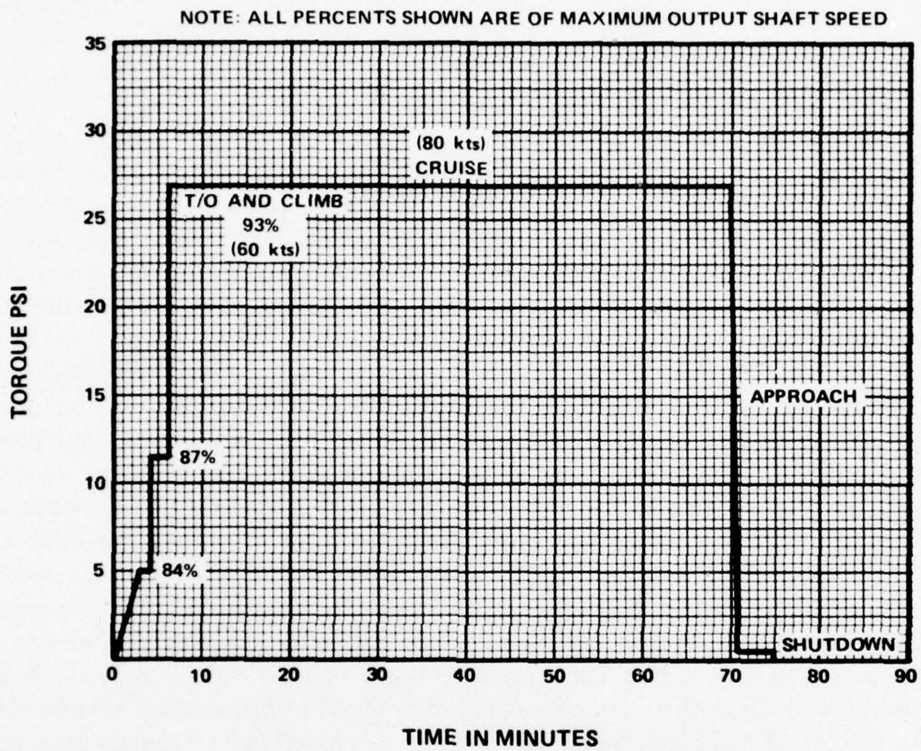


Figure 50. Engine Duty Cycle for Example Analysis

usage should be double-checked for possible corrosion damages caused by seemingly innocuous exposures. The presence of unrecognized residual stress levels can make otherwise corrosion-resistant materials fail prematurely. The design reviews and configuration selections can be considered completed when the agreed-upon design is judged to be consistent with the experience data list and the governing specification requirements.

COMPONENT EVALUATION

Concurrent with or immediately after selecting the design configuration, MAC and FMECA charts are prepared. Samples of these forms appear in Appendixes C and D. The MAC identifies those worn or failed components that cannot be replaced or repaired in the field, thus requiring the engine to be returned to depot. The second group of components, whose failure causes secondary damage which requires the engine to be returned to depot, are identified in the FMECA charts. These components and their failure modes are listed in Tables 20 and 21 respectively.

The predictions for failure and wearout of the components are made by comparison with similar components in other engine applications. Reasonable engine component data for reference purposes was obtained by selecting the UH-1H portion of the T53-L-13A/13B engine data file. The scale factors needed to transform wear life and failure frequencies from the historical data with new component predictions must be derived from a comparison of the engine duty cycles. The average mission engine duty cycle for the UH-1H is shown in Figure 51. A comparison with Figure 50 (example engine duty cycle) shows the following stress relationships: there are only one-half the number of low cycle fatigue (LCF) excursions per operating hour in Figure 50, and the integrated power per unit time (energy) indicates similar heat stress exposure. These stress relationships are used in Tables 20 and 21 in deriving failure and wearlife estimates. Parts which are not field replaceable, causing the engine assembly to be returned to depot, are listed in Table 20, and parts that are field replaceable but have failure modes causing secondary damage, which causes the engine to be returned to depot, are listed in Table 21. The column headings listing the analysis data are identical for both tables. Columns 5, 6, and 7, are labeled Mean-Time-Between-Depot-Returns (MTBDR), Stress Ratio, and Design Margin, are used to relate common component designs with T53-L-13A/13B data. Significant design improvements to be included in the TBO analysis with their effect on reliability are listed in columns 8 and 9. Column 2 lists the Estimated Characteristic Lives that are derived from the design parameters. Design life estimates are based on wear rates, classical spalling (B10 lives) and fatigue stress-cycles. Weibull distribution analysis is used to compute the probability of surviving the specified intervals. Characteristic lives may be in terms of operating hours or stress cycles.

High-cycle fatigues caused by harmonic resonant conditions are usually treated by design to exist above the normal operating rotor ranges. Should they exist below the normal operating range, their fatigue effects are included as part of the low- cycle fatigue limits. Weibull slope parameters used in this analysis vary between 1, (representing a constant hazard rate), and 3 (representing an increasing hazard rate) a Weibull slope parameter of 3 results in a distribution approximating the normal or bell shaped curve. Methods used to estimate Weibull parameters for component failure modes are listed in Appendix E. Although knowledge of the relationship between Weibull parameters and the design criteria is a limiting factor of the component failure mode approach, the continued application coupled with experience and testing feedback data will eliminate the deficiency in the future. Once the failure mode distribution para-

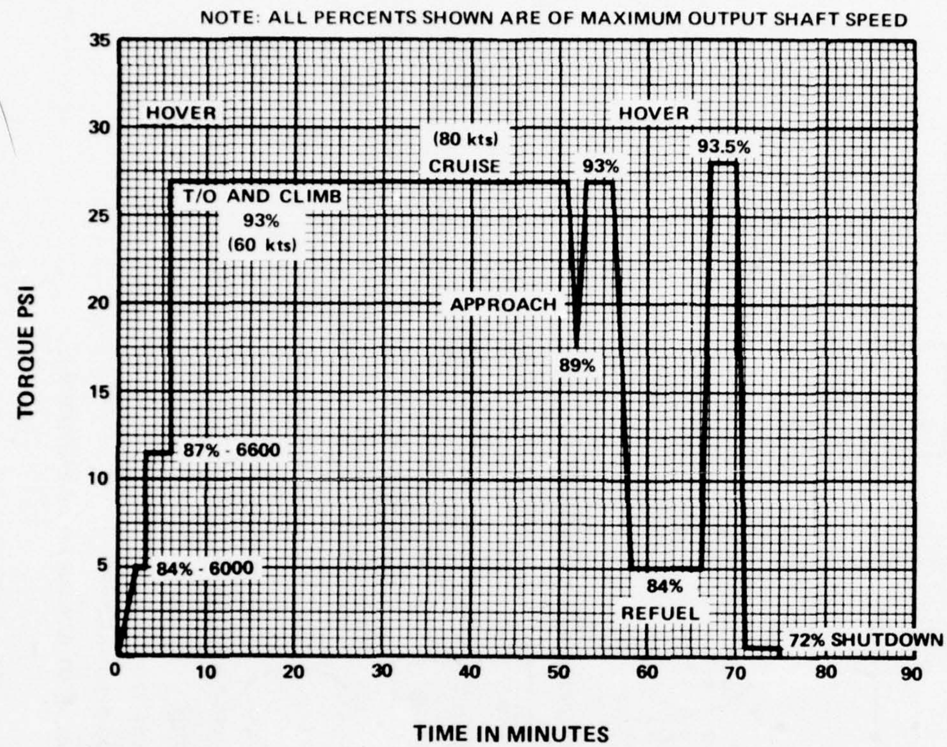
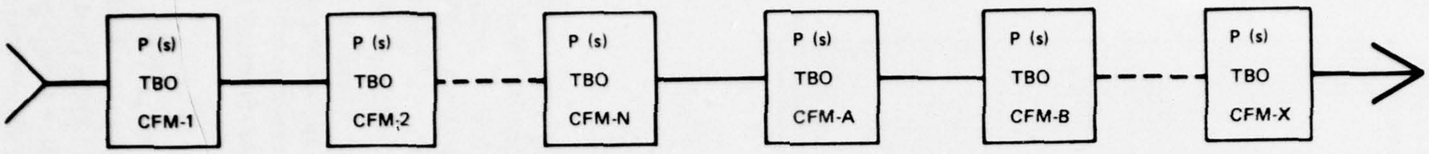


Figure 51. Average Mission for the UH-1H

meters have been derived, probabilities are then computed and listed in columns 10 and 11 (Table 20 and 21) using the Weibull formula P(s) = e exp. $-\left(\frac{t}{\theta}\right)^{\beta}$. The probability of completing 5,000 hours for a component with a shorter recommended replacement interval is conditional. For example, if replacement were recommended at overhaul for a disc with a cycle-limited failure mode, its probability of surviving 5,000 hours would be P(s) 2,000 hours squared times P(s) 1,000 hours. Care must be taken not to treat repetitive time intervals as additive when β is not equal to 1. The models for combining the P(s) 2,000 and P(s) 5,000 are shown in Figure 52. In computing the engine TBO probabilities, data from Tables 20 and 21 are combined and treated as one source.

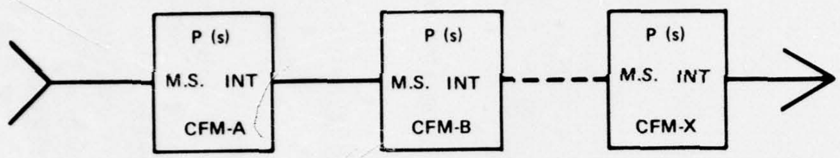
An engine system probability of 90 percent for the 2,000-hour TBO interval, and 99.3 percent for the 5,000-hour TBO interval (mission and safety), is obtained for the example after combining data. This indicates that the proposed engine design just meets the TBO specification requirements. A review of the components shows that the primary limitation of this particular engine in meeting the 2,000-hour interval is the mainshaft

TBO INTERVAL BLOCK DIAGRAM



MATH MODEL. $\left(\prod_{i=1}^{N} P(s)_i\right)\left(\prod_{i=A}^{x} P(s)_i\right)$

MISSION SAFETY INTERVAL BLOCK DIAGRAM



MATH MODEL $\left(\prod_{i=A}^{x} P(s)_i\right)$

NOTE: P (s) = PROBABILITY OF SURVIVING TBO INTERVAL
CFM = COMPONENT FAILURE MODE
M.S. INT. = MISSION SAFETY INTERVAL
I THRU N = FAILURE MODES CAUSING DEPOT RETURN
A THRU X = FAILURE MODES CAUSING DEPOT RETURN AND INPACTING M.S.

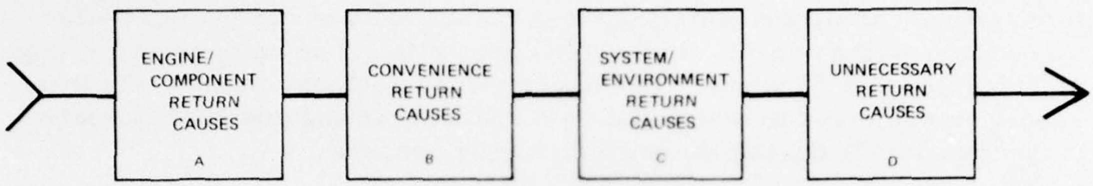
XA-00-446-54

Figure 52. Equivalent Engine System Block Diagram and Math Model

bearings. The primary limiting component in the 5,000-hour interval is the sealing plate on the Number 1 disc. Additional design reviews leading to component improvements for these components would be most effective in improving overall engine TBO capability. The component listings of Tables 20 and 21 should also be used to select those components that should be subjected to additional development testing and quality control inspection levels during the manufacturing process.

SYSTEM TBO INTERVAL PROBABILITIES

It is the overall system depot return causes that drive maintenance cost up, and which can prevent the achievement of engine designed TBO intervals. The benefits of designing and building an engine for extended TBO capability can become lost in a deployment system where nonengine-component causes account for the greater share of depot returns. It is informative and necessary to relate engine-caused returns to environment-caused, unnecessary, and convenience returns. A suggested method is to compare the improved engine related probability of 90 percent for a 2,000-hour probability to the historical composite engine return for all causes shown in Figure 2. These probabilities, as developed, are listed in the model system block diagrams (Figure 53) for comparative purposes. Composite engine environment-caused return frequency was 695 events per million operating hours. Assuming a random distribution, the probability of successfully completing a 2,000-hour TBO interval is e exp. - $(\frac{2,000}{1,439})$ = 25 percent. This value is entered in block C. Similarly, the convenience return rate of 292 per million hours yields a probability of 56 percent, which is entered in block B; and the unnecessary return rate of 121 per million hours yields a probability of 79 percent entered in block D. Assuming independence of events, the expected system probability of achieving 2,000 hours is only 10 percent in spite of the high (90 percent) capability of the engine (see Figure 53, Example A). It is interesting to note that the original composite engine component-caused return rate of 303 per million would have resulted in a depot success interval probability of 55 percent, and a system success probability of 6 percent (see Figure 53, Example B). Thus, an increase of 35 percent in engine-compoennt TBO capability yields only a 4 percent benefit in the system. This means that improvements in environmental protection or a decrease in convenience returns could be more cost effective than engine component improvements. A system model analysis is necessary to establish the engine interval probability for TBO specification requirements.



MATH MODEL

	P_A	x	P_B	x	P_C	x	P_D	=	OVERALL SYSTEM PROBABILITY OF ACHIEVING 2000 HOURS
EXAMPLE A	.90	x	.56	x	.25	x	.79	=	10 PERCENT
EXAMPLE B	.55	x	.56	x	.25	x	.75	=	6 PERCENT

XA-00-446-55

Figure 53. System Block Diagram and Math Model

To summarize, the necessary elements to establish a procedure with reliability interfaces for high initial TBO's are:

1. A specified interval and probability for the engine design requirement which adequately describes the system environments and engine duty cycle.

2. The identification of the component failure modes responsible for depot returns in the subject engine configuration.

3. A Weibull analysis of the components to determine the probabilities associated with each failure mode for reliability and durability. Events which also impact mission accomplishment or safety should be analyzed separately.

4. An engine evaluation, using a model that combines component probabilities into an engine probability for the design interval time.

5. A testing program to substantiate the "designed in" initial TBO capability.

Table 20. Parts Not Field Replaceable,Causing Depot Returns

Part	Possible Failure Modes	Estimated Characteristic Life	Weibull Shape Parameter	Ref. Data T53-L-13A&B Transport Mission			Design Change	C
				MTBDR	Stress Ratio	Design Strength		
Number 2 Bearing Package	Cage Fracture (Fatigue)	-	1.6	437,755 [7](c)	-	2.3X	Material Change	1
	Race Rotation	-	-	766,072 [4]	-	-	Pinning Races	U
	Spalling	-	1.2	-	-	-	-	5
	Fractured Oil Impeller	-	-	-	-	-	-	
	Oil Seal Wear-Coking	-	3.0	11,563 [265]	-	-	Face Seal	2
Gear N_1 Drive	Fracture (Fatigue)	3,621,000 (3)	1.6	2,516,450 [0]	-	-	-	
	Wear Spalling	100,000 (4)	3.0	-	-	-	-	
Gear Assy N_2 Drive	Fracture	3,621,000 (3)	1.6	2,516,450 [0]	-	-	-	
Power Shaft	Fracture	3,621,000 (3)	1.6	2,516,450 [0]	-	-	-	
	Spline Wear	50,000	3.0	-	-	-	-	
Inlet Hsg.	Erosion Wear	20,000	3.0	-	-	-	-	

(a) Probability of successfully completing 2,000 hours of operation without a depot return event.
(b) Probability of successfully completing 5,000 hours of operation without a depot and mission and safety event.
(c) Numbers in [ ] are numbers of occurrences.

aceable,Causing Depot Returns

3 Transport Mission			Redesign				
o	Design Strength	Design Change	Estimated Characteristic Life	(a) P(s) 2000	(b) P(s) 5000	Component Retirement	Notes
	2.3X	Material Change	1,157,000	.999962	.999835	-	Conservative estimate based on new material fatigue life
	-	Pinning Races	Unlimited	-	-	-	Race pinning eliminates this failure mode
	-	-	50,000 (1)	.979207	-	At OVHL (2000 Hr)	(1) Estimated characteristics Life from B10 Life
	-	-	-	-	-	-	There have been no known events in 3,064,291 hours for this design
	-	Face Seal	20,000 (2)	.999000	-	4000 Hr. (On condition)	This design is not LCF sensitive. (2) Estimated from test data. Coking problem eliminated with *face seal configuration*
	-	-	-	.999994	.999973	-	(3) Based on zero failures in 2,516,450 hours 50% Confidence
	-	-	-	.999992	-	-	(4) Classical wear life exceeds this estimate
	-	-	-	.999994	.999773	-	
	-	-	-	.999994	.999973	-	
	-	-	-	.999936	-	-	
	-	-	-	.999000	-	-	

2

Table 20. Parts Not Field Replaceable, Causing D

Part	Possible Failure Modes	Estimated Characteristic Life	Weibull Shape Parameter	Ref. Data T53-L-13A& B Transport Mission			Desig Chan
				MTBDR	Stress Ratio	Design Strength	
Compres-sor Rotor Assy	-	-	-	9,770 [174]	LCF 1/2 Cycles	-	T1 R
T1 Rotor	Fatigue	-	3.0	-	-	-	T1 R
Steel Disc	Fatigue	-	3.0	-	-	-	-
IGV	Wear	-	3.0	3,064,291	-	-	-
Centrifugal Impeller	Fatigue Fracture	28,000 Cycles (5)	B = 3.0	117,857 [26]	LCF 1/2 Cycles	Incr Strength Bending	Thick Blade ECP
	Wear	-	B = 3.0	-	-	-	-
Air Diffuser	Fatigue Cracks	-	B = 2.0	218,878 [14]	1/2 Cycles	-	-
Impeller Bolts	Fracture	-	-	82,819 [37]	-	4X	New Mate & To ing

teplaceable, Causing Depot Returns (Continued)

ort Mission esign Strength	Design Change	Redesign Estimated Characteristic Life	P(s) 2000 [a]	P(s) 5000 [b]	Component Retirement	Notes
-	Tl Rotor	-	-	-	-	Design change from AL. to TI resulted in 0 failures in over 6 million hr
-	Tl Rotor	33,000 Cycles [5]	.999777	.999527	At OVHL (2000 Hr.)	(5) Lower 3σ Value (.999)
-	-	50,000 Cycles [5]	.999936	.999864	At OVHL (2000 Hr.)	
-	-	30,000	.999704	-	On Condition At OVHL	
r Strength nding	Thicker Blades ECP	-	.999636	.999226	At OVHL (2000 Hr.)	
-	-	50,000	.999936	-	On Condition At OVHL	
-	-	Thermal 20,000 Cycles	.990050	-	On Condition At OVHL	
4X	New Material & Torque-ing	Unlimited	-	-	-	Failure mode eliminated

Table 21. Field Replaceable Parts With Failure Modes Cau

Part	Possible Failure Modes	Estimated Characterisic Life	Weibull Shape Parameter	Ref. Data T53-L-13A&B Transport Mission: MTBDR	Stress Ratio	Design Margin	Design Change	Red Est Chara L
No. 21 Bearing	Roller Skewing	-	-	119,831 [21] (c)	1/2 Cycles	-	E.O. 80313 Incr Roller End Rad.	Unlim
	Spalling	52,000 (1)	1.2	-	-	-	-	-
No. 21 Bearing	Cage Fracture (Fatigue)	-	1.6	359,493 [7]	1/2 Cycles	2.3X	Cage Material Change	950
	Race Rotation	-	-	81,176 [31]	-	-	Pinning Races ECP	Unli
	Spalling	260,000 (1)	1.2	148,026 [17]	-	-	-	-
No. 4 Bearing	Cage Fracture (Fatigue)		1.6	838,817 [3]	1/2 Cycles	2.3X	Cage Material Change	2,200
	Spalled	50,000 (1)	1.2	629,113 [4]	-	-	-	-
Compressor Blades	Fracture (Fatigue)	3,621,000	1.6	2,516,450 [0]	1/2 Cycles	-	T1 Rotor	-
Sun Gear	Fatigue Fracture	3,621,000	1.6	2,516,450 [0]	1/2 Cycles	-	-	-
Blade No. 1 G.P. Turb.	Fatigue	2,800,000	1.6	2,516,450 [1]	1/2 Cycles	-	-	-
Retainer No. 1 G.P. Turb.	Unseated	-	-	2,516,450 [1]	-	-	Change Cooling Syst.	-

(a) Probability of successfully completing 2,000 hours of operation without a depot return event.

(b) Probability of successfully completing 5,000 hours of operation without a depot and mission sand safety event.

(c) Numbers in [ ] are numbers of occurrences.

ble Parts With Failure Modes Causing Depot Returns

port Mission sign Margin	Design Change	Redesign Estimated Characteristic Life	(a) P(s) 2000	(b) P(s) 5000	Component Retirement	Notes
-	E.O. 80313 Incr Roller End Rad.	Unlimited	-	-	-	Failure mode eliminated
-	-	-	.980153	-	On Condition At OVHL	Depot return for oil contamination (1) Based on B10 life
2.3X	Cage Material Change	950,000	.999948	.999774	-	Conservative estimate based on improved material
-	Pinning Races ECP	Unlimited	-	-	-	Failure mode eliminated
-	-	-	.997098	-	On Condition At OVHL	Depot return for oil contamination
2.3X	Cage Material Change	2,200,000	.999986	.999941	-	
-	-	-	.979207	-	On Condition At OVHL	Depot return for oil contamination
-	T1 Rotor	-	.999994	.999973	On Condition At OVHL	Based on 0 failures 2,516,450 hours.
-	-	-	.999994	.999973	On Condition At OVHL	Based on 0 failures 2,516,450 hours
-	-	-	.999991	.999960	-	
-	Change Cooling Syst.	-	-	-	-	Failure mode eliminated

Table 21. Field Replaceable Parts With Failure Mo

Part	Possible Failure Modes	Estimated Characteristic Life	Weibull Shape Parameter	Ref. Data T53-L-13A&B Tranport Mission			Des Cha
				MTBDR	Stress Ratio	Design Margin	
Blade 1st P.T.	Fatigue	2,800,000	1.6	2,516,450	LCF 1/2 Cycles	-	-
Fuel Control	P1 Bellows Fracture	-	3.0	2,516,450 [1]	-	4X	Stai Stee Bel
	Drive Spline Wear		3.0	838,817 [3]	-	3X	Inc Dri gag
No. 3 Bearing	Spalling	100,000	1.2	-	-	-	-
	Rate Rotation	-	-	-	-	-	-
	Plating Adhesion Oil Impeller	-	-	2,516,450 [1]	-	-	-
G.P. Nozzle	Thermal Fatigue Cracks	-	3.0	2,516,450 [1]	-	-	-
G.P. Turbine No. 1 Disc	Fatigue	100,000 Cy.(2)	3.0	-	-	-	-
G.P. Turbine No. 2 Disc	Fatigue	22,000 Cy.(2)	3.0	-	LCF 1/2 Cycles	-	-
P.T. Turbine No. 1 Disc	Fatigue	100,000 Cy.(2)	3.0	-	LCF	-	-
P.T. Turbine No. 2 Disc	Fatigue	-	3.0	-	1/2 Cycles	-	-

arts With Failure Modes Causing Depot Returns (Continued)

port Mission esign Margin	Design Change	Redesign Estimated Characteristic Life	(a) P(s) 2000	(b) P(s) 5000	Component Retirement	Notes
-	-	-	.999991	.999960	On Condition Field.	
4X	Stainless Steel Bellows	Unlimited	-	-	-	Failure mode eliminated
3X	Increased Drive Engagement	Unlimited	-	-	-	Oil contamination and power loss
-	-	-	.990896	-	On Condition At OVHL	Depot return for oil contamination
-	-	-	-	-	-	Failure mode eliminated
-	-	-	-	-	-	Silver plating removed from impeller
-	-	8,000	.984496	-	On Condition Field	Slight rub caused depot return
-	-	-	.999992	.999875	5000 Hr. Field	(2) Estimated cycle life is lower $3\ \sigma$ value (.999 Confidence)
-	-	-	.999249	.998405	2000 Hr. Field	
-	-	-	.999992	.999875	5000 Hr. Field	
-	-	22,000 Cy.(2)	.999249	.998405	5000 Hr. Field	

Table 21. Field Replaceable Parts With Failure Modes Causing D

Part	Possible Failure Modes	Estimated Characteristic Life	Weibull Shape Parameter	Ref. Data T53-L-13A&B Transport Mission			Design Change	
				MTBDR	Stress Ratio	Design Margin		
Sealing Plate No. 1 Disc	Fatigue	-	3.0	-	LCF 1/2 Cycles	-	-	
Oil Pump	Impeller/ Shaft Fracture Fatigue	2,800,000	1.6	2,516,450 [1]	LCF 1/2 Cycles	-	-	

Parts With Failure Modes Causing Depot Returns (Continued)

Transport Mission		Design Change	Redesign Estimated Characteristic Life	P(s) 2000[a]	P(s) 5000[b]	Component Retirement	Notes
	Design Margin						
	-	-	25,000 Cy.[2]	.999488	.998913	Field (2000 hr)	
	-	-	-	.999991	.999960	-	

3.0 EVALUATION OF ADVANCED DEVELOPMENT CONCEPTS

AEROTHERMODYNAMIC COMPONENTS

The development of gas turbine technology has consistently pursued the objective of improving specific fuel consumption (sfc). Today, the higher cost of fuel has generated an additional incentive for the development of fuel conservative engines.

The main design means of achieving lower sfc consists of increasing both cycle pressure ratio and turbine inlet temperature. Therefore, all aerothermodynamic means for a better sfc are inherently conducive to lower engine reliability. Increasing component efficiency also contributes to improved engine sfc; however, progress by this method is limited since component efficiencies have already reached a high level.

COMPRESSOR

To achieve higher cycle pressure ratios, compressors must be designed with an increased number of stages and with additional part-load alleviating devices such as variable geometry stators and airbleed provisions. Therefore, because this results in additional bulk and weight, compressor design has leaned toward the reduction of the number of stages by increasing the individual stage pressure ratio. This concept applies to centrifugal as well as to axial stages. Since there are stringent physical limits to the specific aerodynamic blade loading that can be achieved without introducing an efficiency penalty, advanced compressors are designed for increasingly higher rotational speeds and higher airflow velocities. Consequently, the blade and disc stress levels increase continually, while the relative thickness of the blade profiles decreases to accommodate the resultant higher Mach numbers. As a result, not only do the blades become more susceptible to erosion and other foreign object damage, but the stage and the compressor surge margins decrease. The higher loadings now associated with higher Mach numbers at the blades may generate stronger blade and disc vibratory excitations. Higher vibration modes were deemed harmless heretofore. Now they must be avoided, together with the more conventional first-shaft bending and torsion modes, over a wide engine operating range. Moreover, maintaining high efficiency while using high aerodynamic blade loadings requires a reduction of the blade tip clearances that substantially increases the danger of destructive blade casing rubs.

Axial Compressor Materials

In smaller engines, the trend will be toward integrally cast in lieu of separately bladed axial stages of "HIP Custom 450" material. Consequently, field replacement of compressor blades will not be possible. The general corrosion resistance of this material will be slightly improved over that of other semiaustenic stainless steel such as "17-4PH", "AM350", "AM 355", and it will be superior to that of other martensitic stainless steels; e.g., "410" and "Greek Ascology". HIP Custom 450's high-cycle fatigue (HCF) performance is excellent and will exceed that of wrought titanium and nickel-base alloys (the most commonly used material for compressor blades).

Compressor cases made of cast magnesium will continue to be used where temperature and pressures permit. Even though prior experience has been acceptable, some improvement in corrosion protection systems will be incorporated. This will have the effect of improving structural integrity at minor increases in cost. To cope with temperature and pressure increases associated with advanced thermodynamic cycles, cast titanium cases will most likely be used for the radial compressor stage because they will provide excellent structural integrity and very low maintainability costs, since no corrosion protection systems will be required.

Erosion resistance for a given material can be improved through the use of a hard coating. A powdered-metal (PM) superalloy such as "PA101" has demonstrated that it has the best inherent resistance to erosion and corrosion of all other potential compressor materials examined. The use of PM would involve separately bladed rotors and thus result in higher costs than those integrally cast with HIP Custom 450. Another advantage of PM blades is that they would be field replaceable.

Currently, programs exploring low-cost approaches to blade manufacture and attachments are in progress. The attachment concepts involve loose tolerance for low cost and the use of a potting material. This attachment concept has been demonstrated, and while field replacement of individual blades may not be possible, repair at a depot is possible. This concept offers the potential of reducing overall system costs through improved maintainability for those applications where separately bladed rotors are necessary.

Centrifugal Compressor

The use of wrought titanium will continue to be used for most centrifugal impeller applications. As temperatures increase, improved alloys such as Ti-6246 will be used. For smaller engines, investment cast impellers of alloys such as HIP Custom 450 are likely to be used for reasons of cost. Maintainability for either case should continue to be excellent.

Compressor Reliability Assessment

The danger of higher disc and blading stresses is generally met satisfactorily by the use of higher quality materials; i.e., materials with higher specific and absolute strength capability, such as titanium and steel. Hence, higher steady-stress levels will have little impact on the operational reliability of advanced compressors.

The structural weakness of relatively thin blades can be partially suppressed by selecting larger blade chords, thus keeping the absolute thickness of the profiles large enough to afford sufficient resistance to corrosion and effects of foreign object impact and, at the same time, maintain the close dimensional tolerances necessary for efficient operation. Lower blade aspect ratios also contribute to the minimum action of the surge margin deterioration experienced in highly loaded stages. The advanced blade configurations of highly loaded, high Mach number stages will have only moderate adverse impact on operational reliability.

The danger of blade tip/casing rubbing can be avoided partially by the detailed evaluation of the differential rotor end casing radial dilations, abradable casing coatings, and shroud insert materials that minimize the frictional effects. However, the asymmetric deformation of the compressor casing caused, for instance, by the presence of structural elements crossing the flow paths and by engine mount forces constitutes an operational hazard that may have a substantial, adverse impact on the reliability of advanced, high-pressure ratio compressor.

The danger of high vibrational stresses can only be partially avoided by the use of low-aspect ratio blades. In spite of increasingly detailed analytical investigations, it is virtually impossible to avoid resonant excitation for all critical vibratory modes over a wide engine-operating range. As a result, higher blade excitation forces may substantially degrade advanced compressor reliability.

The danger of lower surge margins obviously must be assessed at the engine design stage. During engine development, components are correctly matched to avoid compressor surge. However, as component performance deteriorates, the requirement to maintain engine power may cause the compressor to operate closer to its surge limit. Therefore, premature deterioration of surge margin constitutes an increased operational hazard of advanced compressors.

The impact on operational reliability of advanced design concepts presently in development for high-pressure ratio compressors can be minimized by improved mechanical design provisions and by operation-monitoring techniques. However, since all mechanical problems may not be corrected during the engine qualification stage and the capability of on-board monitoring equipment is limited, it is possible that the reliability of high-pressure ratio compressors will be adversely affected by the advanced design provisions currently envisioned to improve engine specific fuel consumption.

TURBINE

To withstand higher inlet temperatures, turbines must be designed with improved materials and cooling provisions. Hence, it is necessary to increase the amount of cooling air extracted from the compressor for two reasons:

1. A larger quantity of heat must be removed from the hot metal parts because of the higher gas temperature.

2. The pressure level of the cooling air tends to increase as cycle pressure ratio increases, and the air temperature, consequently, tends to increase.

Since a substantial aerodynamic performance penalty is associated with cooling, the tendency is to minimize the amount of cooling air and to operate the turbine with metal temperatures closer to the material's strength limits. Moreover, as cycle temperature increases, circumferential temperature distortions at turbine inlet become more critical. Temperature peaks must be minimized to avoid critical hot spots on stators and other stationary turbine elements.

Like compressors, modern turbines are designed with increasingly higher aerodynamic loadings that generate stronger blade and disc vibratory excitations. Keeping a high efficiency also requires tightening of the blade tip clearances and leads to designs with minimum trailing-edge thickness, which substantially increases the sensitivity of cooled blades to temperature erosion. Higher rotational speeds also result in higher stress levels.

Turbine Discs

It is anticipated that PM turbine discs will be widely used in future engines. These discs have the potential of being lower in cost, as a result of simplified fabrication practices, having lower material input weight and being more amenable to ultrasonic inspection because of their finer grain size and more uniform structure. The latter attribute will provide a higher level of quality in turbine discs and, thereby, improve reliability. PM superalloys will provide improved turbine disc life due to their higher mechanical properties, specifically better low-cycle fatigue life, and stress-rupture strength.

Turbine Blades

The next-generation turbine engines will involve the wider application of directionally solidified (DS) superalloys for turbine blades. These materials will offer nominally 40° to 50°F improvement in temperature capability over their conventionally cast counterparts. The main advantages of DS blades will be greatly improved thermal fatigue resistance. Oxidation and sulfidation resistance of DS castings will be equivalent to conventional castings, whether coated or bare, since environmental resistance is a function of composition. For improved maintainability, practices to strip, inspect, and recoat blades can be developed to reduce maintenance costs.

Turbine Reliability Assessment

The following concepts are used to enhance the reliability of advance engine design: improved materials, lower blade aspect ratio, and controlled growth rates of rotors and casings.

The problems in the turbine, however, are much more serious than in the compressor. Recent experience of the airlines using the new generation of high-temperature fan engines clearly shows that the mechanical integrity of the hot-engine sections has been sacrificed in spite of the progress of metallurgy, cooling techniques, and analytical prediction and design methods.

It is probable that more serious mechanical problems will escape detection in the turbine than in the compressor section at the engine qualification stage. Therefore, the reliability of advanced turbines is likely to be seriously affected if the turbine inlet temperature increases beyond the 2,240° to 2,420° F level presently used in the most advanced turbine designs.

POWER MANAGEMENT

For multi-engine fixed-wing aircraft and helicopters, the engine life can be increased and maintenance reduced by using full-rated power only as a reserve that is automatically available if loss of engine occurs during the critical takeoff and hover flight modes. This power control system would allow the engines to be operated at less than full-rated power on a day-to-day basis, while maintaining full takeoff performance of the aircraft. The system can be applied to both fixed-wing aircraft and helicopters. For fixed-wing aircraft with two or more turboprop or turbofan engines, the power control system would sense the loss in power of the failed engine through a drop in torque or rpm. The remaining engines' fuel control unit would be signalled automatically to increase power.

In helicopters, the loss of engine power would signal the remaining engines to make power available on demand through the normal pitch control without diverting the pilot from his emergency procedures.

CERAMIC COMPONENTS

The use of ceramic components in turbine engines will be paced by the ability to resolve the metal/ceramic design problems. The application of ceramics in turbine vane and turbine cylinder applications has a reasonable potential of success and can provide reduced fuel consumption with greatly improved oxidation and sulfidation resistance. The application of ceramics in rotating hardware is a much greater risk and is paced by the development of ceramics with improved FOD resistance. The tendency for carbon build-up in the combustor means the ceramic blades must at least be resistant to carbon-particle impace damage. It is anticipated that particle separators can be employed to effectively screen out ingested particles large enough to be harmful. Ceramic components of this type will not be available for several years.

BEARINGS

Advanced engines operating at high pressure ratios will have stiffer shafting systems to forestall critical speed problems. These shafting systems will require larger bearings and, therefore, bearing DN (diameter in mm x speed in rpm) values will increase even though shaft speeds may not be higher. It is anticipated that DN values will increase from the present 2×10^6 to 3×10^6.

For high-speed ball bearings, development of optimum cooling and lubrication will be of prime importance. Work is also required on optimum internal geometry, higher-strength cages, reduced weight, and reduced cage friction.

Ball bearings require a minimum thrust load to prevent skidding; however, if thrust loading is excessive, fatigue failure will result. Analytical and experimental work is required to establish minimum bearing loading. In addition, improved methods to calculate bearing thrust loading due to aerodynamic forces are required as well as new measuring techniques to verify thrust loading in engine operation.

High-speed roller bearings will require more development than ball bearings. The major problem is roller end wear leading to cage failure. Improved lubrication and bearing geometry must also be pursued.

During the next 10-year period, new roller bearing concepts may become available, such as the dual-diameter or hybrid bearings.

New compressors will lead to the use of supercritical speed main shafts and intershaft bearings. Because it is difficult to lubricate intershaft bearings, this development may hasten the advent of air bearings. The foil bearing, an air bearing design with the advantage of some tolerance to shaft motion, should be considered for intershaft or mainshaft applications. Additional development and analysis in the areas of intershaft bearings and air bearings are required.

Increasing use will be made of bearing designs that do not require oil-jet lubrication, such as grease-packed, mist-lubricated, or air bearings, particularly in accessory drives.

SEALS

Advanced engines in the 3- to 10-lb/second class incorporate mainshaft seals that operate with surface speeds up to 450 ft/second, air pressures up to 104 psia, and air temperatures to 1,000°F. Positive-contact carbon seals are used. In future high-performance engines, seal operating conditions will be more severe, and existing positive-contact seal configurations may not be adequate. At high speeds and pressures, positive-contact carbon seals have a tendency to wear, generate heat, and coke up.

An alternative to positive-contact seals is labyrinth seals. Because of their noncontacting feature, labyrinth seals offer infinite life; however, at high air pressures and temperatures, simple labyrinths will not suffice, and complicated multistage labyrinths must be used. These latter seals incorporate venting and pressurization passages that are costly to produce and difficult to accommodate in small, high-performance engines. Compared with positive-contact seals, labyrinths also permit higher leakage airflows (which must be absorbed by the lubrication system, which in turn causes a loss in engine performance).

The NASA self-acting seal concept incorporates the best features of positive-contact seals (low leakage) and labyrinth seals (noncontacting). During operation, self-acting seals are noncontacting, the sealing surfaces being separated by a thin gas film (sealing gap) that limits gas leakage. At shutdown the seal is positively contacting. Self-acting seal designs incorporate Rayleigh step lift pads on the primary (carbon) sealing faces. These lift pads provide hydrodynamic force to separate the sealing surfaces, and the gas film is sufficiently stiff so that the primary (carbon) ring tracks the runout motions of the seat without rubbing contact. Lycoming has been working with NASA in the development of self-acting gas-film face seals. Performance of this seal has been demonstrated at pressure differentials of 250 psi and speeds to 600 fps.

Present carbon seals exhibit satisfactory oxidation resistance to 900°F. As operating temperatures increase, higher temperature carbon seals will be required. The problem encountered today at high temperatures is coking on the oil side of the carbon segments. Therefore, increases in temperature will be paced by the introduction of new fluids with higher coking temperatures.

Magnetic fluid seals, a new development, will be evaluated for application in cool turbine positions such as output shaft seals and gearbox seals. Another potential application for this configuration will be as a shaft seal for the vacuum chamber of a composite flywheel installation.

GEARS AND CLUTCHES

The gear material (SAE 9310) presently used in the industry is fully developed and does not offer any potential for an increased load carrying capability. Tool steels such as VASO X2, which will be introduced in the coming decade, offer substantial improvement in compressive stress and flash temperature rise. In addition, the high temperature hardness of tool steel offers improvement in the area of oil interruption operation.

To date, VASCO X2 has been applied in the Boeing Vertol Company heavy-lift and UTTAS transmissions. Problems occurring in the heat treatment of this carburized steel apparently have been resolved. Application of tool steels to gas turbine gearing offers good potential for uprating gear sets without increasing envelope size.

Gear data for engineering drawings are presently transferred by hand from computer output sheets. A computer program can be developed to automatically produce gear data on engineering drawings and also to provide cutting-tool geometry. Present analytical programs can be expanded to include finite-element techniques to calculate gear tooth deflections and stresses.

New concepts in overrunning clutches, such as the spring clutch and the positive-engagement clutch, may be introduced in military helicopter transmissions. These designs must be evaluated for use in engine applications.

BEARINGS, SEALS, AND GEARS - RELIABILITY ASSESSMENT

The probable effect on flight safety and mission reliability of the next generation of engine components, including bearings, seals, and gears, is difficult to assess at this time. Unquestionably, these components must be as reliable as the current state of the art permits. A conservative approach dictates that, with increased operating temperatures, speeds, and pressures, these components are not likely to be much better than what we have today. Yet the contemporary turbine engine itself operates at higher temperatures, speeds, and pressures than its predecessors and is at the same time more reliable.

Avco Lycoming believes the reliability of any of these components will only be as good as that required by the procurement specification because performance will undoubtedly continue to be the overriding criterion. Specifying wearout rates for all components will not only improve flight safety and mission reliability but will also reduce the number of depot returns. Procurement specifications should include appropriate components and complete engine test requirements that will verify these design and reliability goals.

LUBRICATION SYSTEM

A mathematical model defining an engine lubrication system as a flow and pressure network is being developed under Lycoming's 1977 Independent Research and Development Program. This effort will enable parametric studies to be conducted, showing the effect on the total system of changes in any branch of the system. Heat rejection to the lubrication system will be calculated as a function of power, altitude, ambient temperature, and oil temperature.

By using the model or analytical tool described above, an integrated lubrication system, pump, filter, tank and cooler will be developed for advanced engines. In the present application, the oil tank and cooler are usually supplied by the airframe manufacturer. This integrated lubrication system will contain a high-speed oil pump that operates at speeds above 15,000 rpm, compared with today's 6,000-rpm pump which will eliminate the need for speed-reduction gearing. The technology for high-speed pumps was developed in Avco Lycoming's contributing Engineering Programs and is presently available as report number 3195.4.13.

REFERENCES

1 Bates, V., "T53 Reliability and Maintainability Quarterly Progress Report," Avco Lycoming, Report Number 1625.5.12 U.S. Army Aviation Systems Command, St. Louis, Missouri, December 1973.

2 Lipnickas, J., "T53 Reliability and Maintainability Evaluation Program," Avco Lycoming, Report Number 1628.5.15 U.S. Army Aviation Systems Command, St. Louis, Missouri, November 1974.

3 Cardinale, R., "T55 Reliability and Maintainability Quarterly Progress Report," Avco Lycoming, Report Number 1755.5.37 U.S. Army Aviation Systems Command, St. Louis, Missouri, March 1976.

4 Hohenberg, R., "The Engine Usage Indicator, An Instrument to Assess the Expenditure of Useful Gas Turbine Life," Fourteenth International Gas Turbine Conference, Cleveland, Ohio, March 1969.

5 U.S. Aviation Systems Command, "Management Summary Report AH-1G," Technical Report 72-28 U.S. Army Aviation Systems Command, St. Louis, Missouri, July 1972.

APPENDIX A

BASIC DATA

Figures A-1 through A-5 provide the listings of basic return data as categorized from the Avco Lycoming engine data bank. These lists, one for each engine model, are the basis from which this report was prepared.

Table A-1 provides a convenient comparison of the return rates for the engine models studied. These return rates are in terms of returns per million operating hours.

Table A-2 lists the composite engine return rates. This table permits comparison between any specific engine against the "normal" engine.

Table A-3 lists the composite engine (military models only) and allows comparisons, return rate-wise, with the civil composite rates in Table A-4.

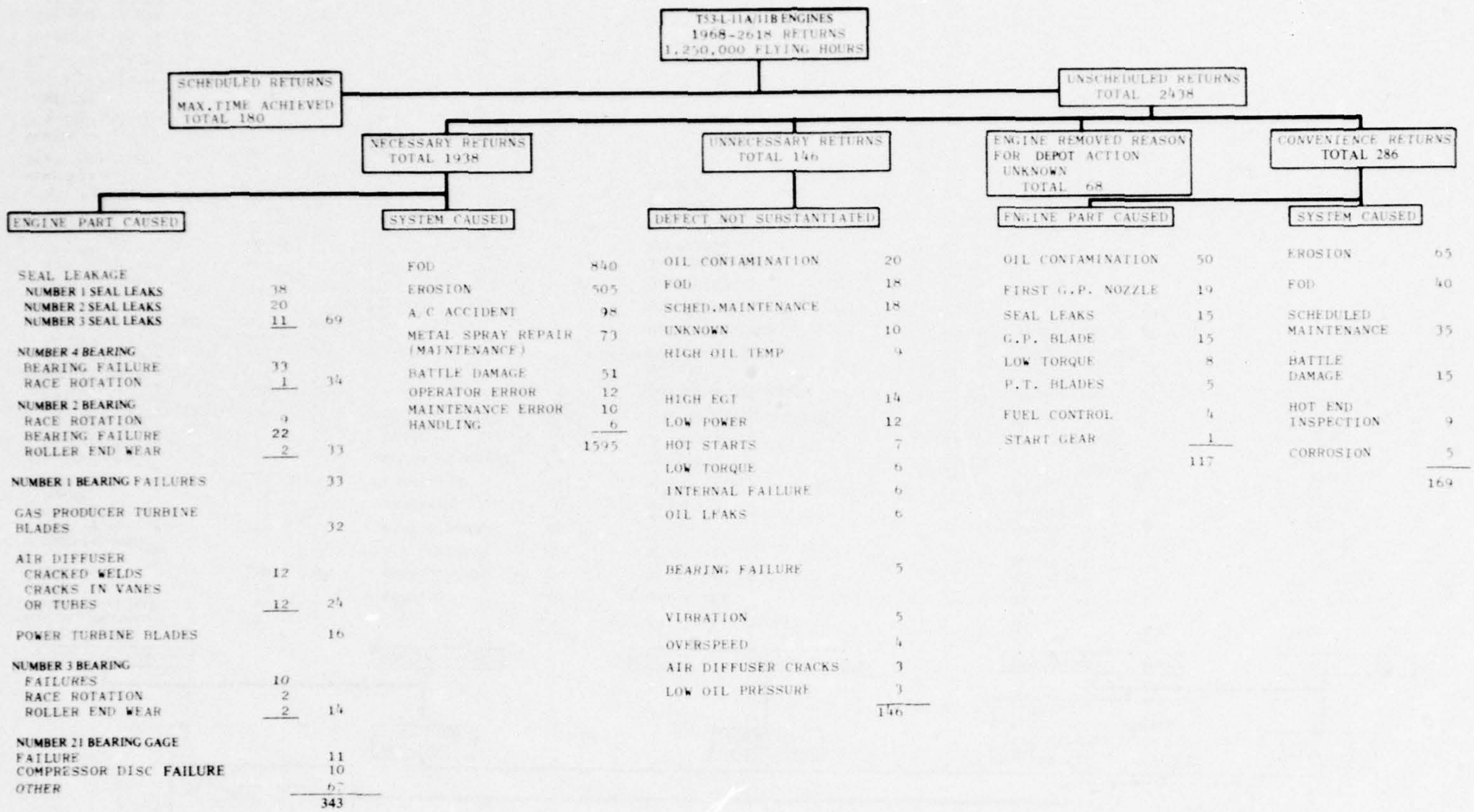


Figure A-1. T53-L-11A/11B Basic Data

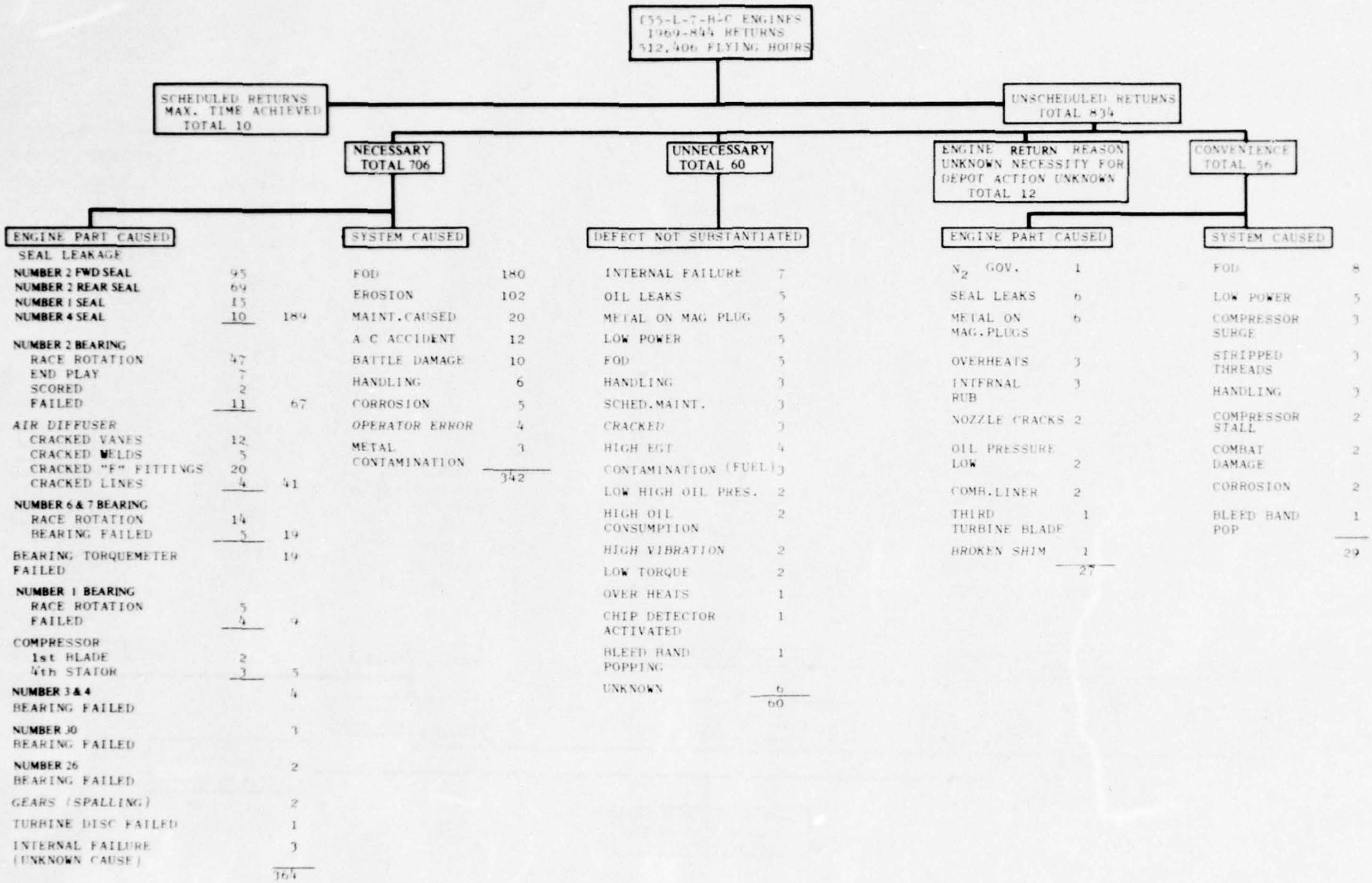


Figure A-2. T55-L-7 Basic Data

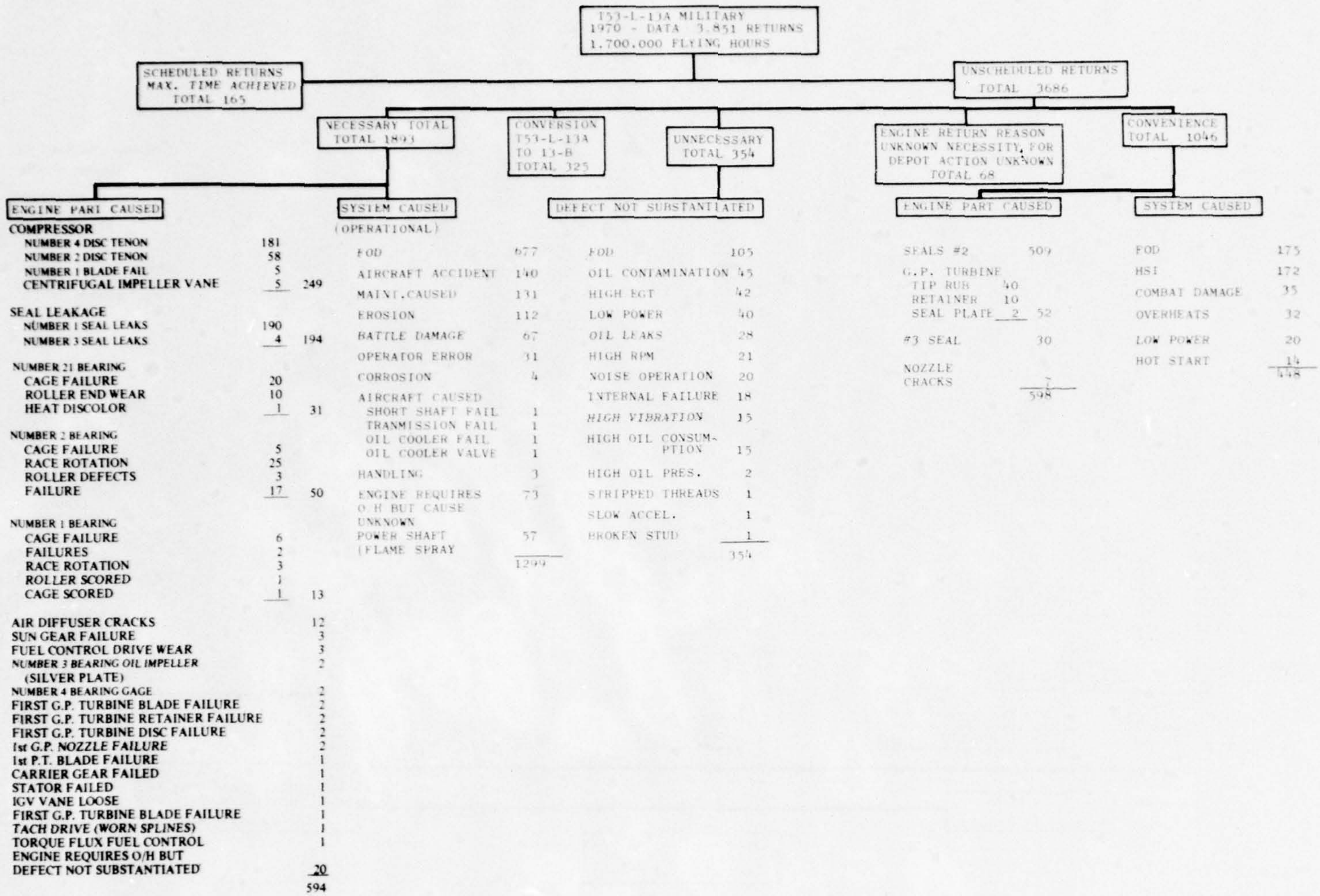


Figure A-3. T53-L-13A Basic Data

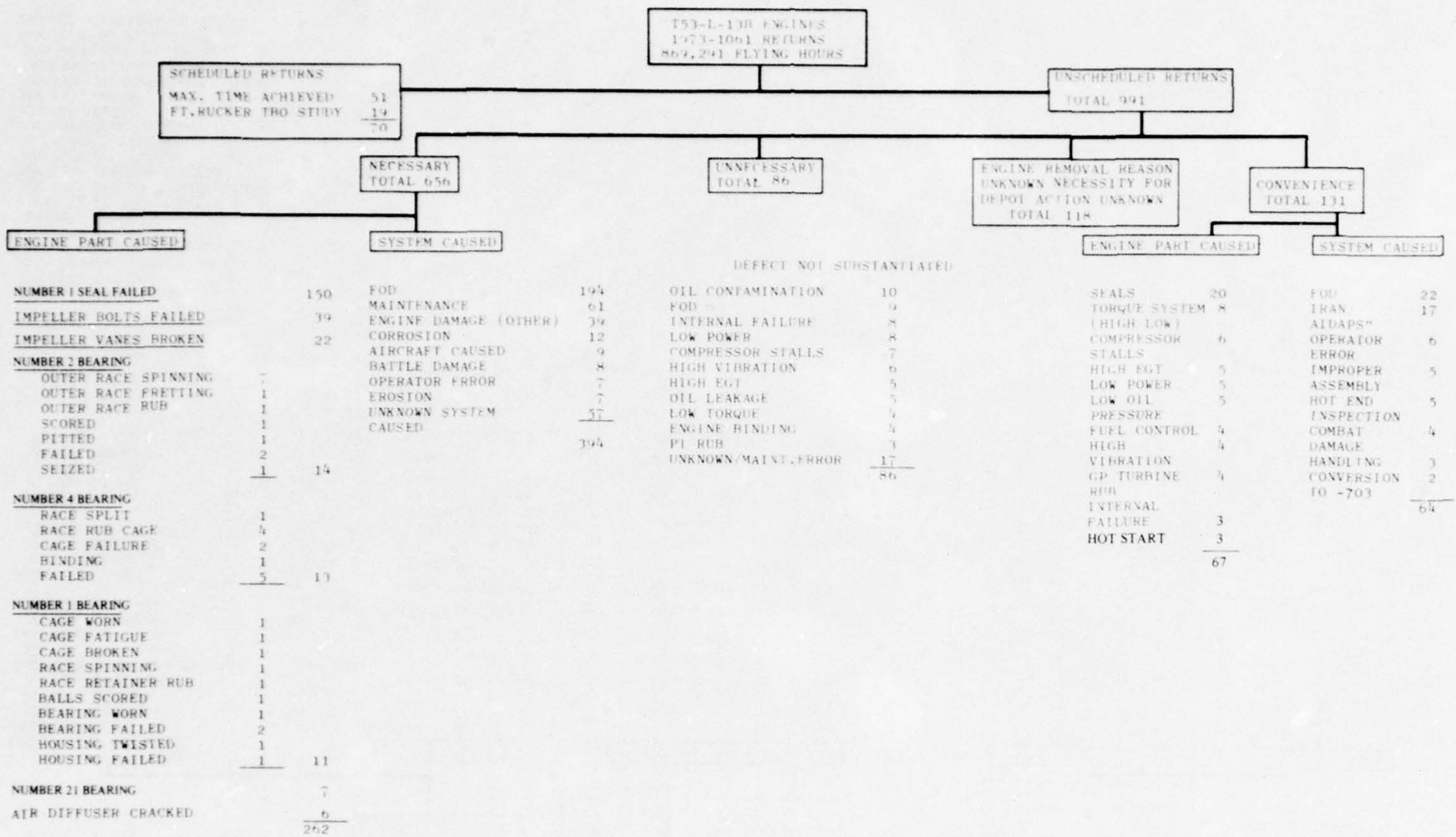


Figure A-4. T53-L-13B Basic Data

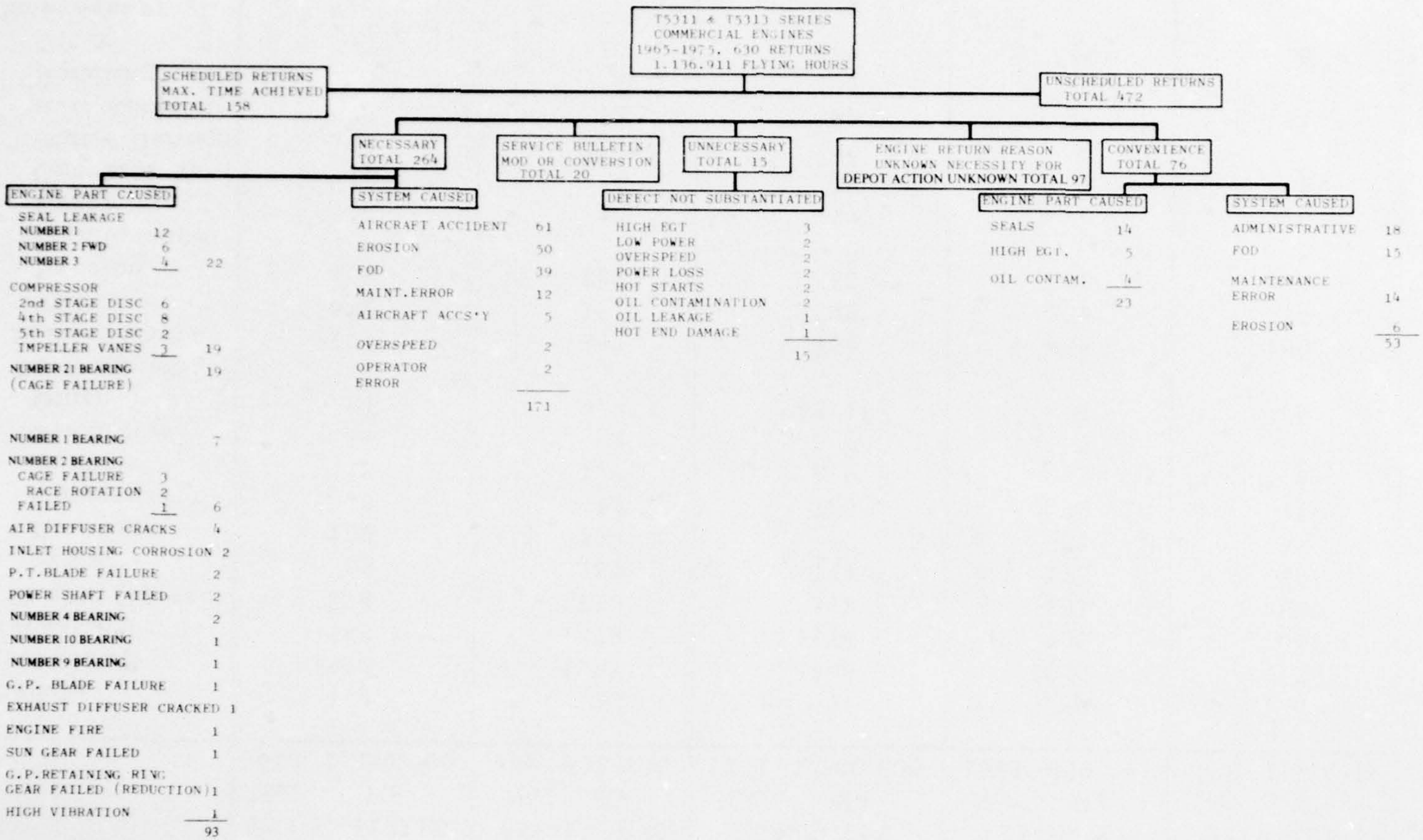


Figure A-5. Commercial Basic Data

Table A-1. Depot Return Rates of All Engines Per Million Operating Hours

	1968 T53-L-11/11B No. Hr 2618 1,250,000	1969 T55-L-7B/C No. Hr 844 512,406	1970 T53-L-13A No. Hr 3851 1,700,000	1973 T53-L-13B No. Hr 1061 859,291	1965 - 1975 T5311-T5313B No. Hr 630 1,136,911
Scheduled	144	20	97	58*	139
Unscheduled	1950	1628	2168	1140	415
Necessary	1550	1378	1114	755	264
Engine Caused	274	710	348	301	82
Seals	55	369	114	173	19
Bearings	100	240	57	51	38
Compressor	8	10	125	70	17
Turbine	38	1.9	2.9	-	3.5
Air Diffuser	19	80	7	7	4
Other	54	9.7	42.1	7	.5
Environmental/ System Caused	1276	667	764	453	150
FOD	672	351	398	223	34
Erosion	404	102	66	8	44
Maintenance Error	66	39	77	70	10
Operator Error	10	9	18	8	2
Battle Damage	41	20	39	9	-
A/C Accident	78	12	82	-	54
Handling	5	6	1.7	-	-
Other	-	16	114.3	135	6
Unnecessary Returns (Defect Not Substantiated)	117	117	208	99	13

Table A-1. Depot Return Rates of All Engines Per Million Operating Hours (Continued)

	1968 T53-L-11/11B No. 2618 Hr 1,250,000	1969 T55-L-7B/C No. 844 Hr 512,406	1970 T53-L-13A No. 3851 Hr 1,700,000	1973 T53-L-13B No. 1061 Hr 859,291	1965 - 1975 T5311-T5313B No. 630 Hr 1,136,911
Oil Contamination	16	10	26	12	1.7
Internal Failure	5	14	11	9	-
FOD	14	10	62	10	-
Low Power	10	10	24	9	1.7
High EGT	11	8	25	6	3
Other	61	65	60	53	7
Engine Removed, Reason for Return Unknown	54	23	40	136	85
Convenience Returns	229	109	615	151	67
Engine Caused	94	53	352	77	20
Oil Contamination	40	12	-	-	3.5
Seals	12	12	317	23	12
Nozzle Cracks	15	4	4	-	-
Turbine	16	1.9	31	5	-
Other	10	9.1	-	-	4.5

Table A-1. Depot Return Rates of All Engines Per Million Operating Hours (Continued)

	1968 T53-L-11/11B No. Hr 2618 1,250,000	1969 T55-L-7B/C No. Hr 844 512,406	1970 T53-L-13A No. Hr 3851 1,700,000	1973 T53-L-13B No. Hr 1061 859,291	1965 - 1975 T5311-T5313B No. Hr 630 1,136,911
System Caused	135	57	264	74	47
FOD	32	16	103	25	13
Erosion	52	19	-	-	5.2
Hot Section Insp.	7	-	101	6	-
Adminis-trative	-	-	-	20	16
Other	23	22	60	23	12.8
Conversion To Other Models	-	-	191	2	18
Totals	2094	1647	2265	1221	554

* Depot return rate includes 22 engines used in Ft. Rucker TBO study.

Table A-2. Summary Matrix Composite Engine - All Engines

Cause of Return	Necessary			Convenience			Total		
	Number	(%)	Rate $X10^6$	Number	(%)	Rate $X10^6$	Number	(%)	Rate $X10^6$
Engine/ Component									
Seal (Mainshaft)	623	6.92	113.9	594	6.60	108.6	1217	13.52	222.5
Bearings (All Causes)	491	5.45	89.8	60	.67	11.0	551	6.12	100.8
Race Rotation	117	1.30	21.4	-	-	-	-	-	-
Cage Defects	55	.61	10.1	-	-	-	-	-	-
Roller Defects	19	.21	3.5	-	-	-	-	-	-
Compressor (All Causes)	334	3.71	61.1	6	.07	1.1	340	3.78	62.2
Blades	7	.08	1.3	-	-	-	-	-	-
Discs	225	2.50	41.1	-	-	-	-	-	-
Vanes	30	.33	5.5	-	-	-	-	-	-
Bolts	39	.43	7.1	-	-	-	-	-	-
Stators	4	.04	.7	-	-	-	-	-	-
Air Diffuser (All Causes)	87	.97	15.9	-	-	-	-	-	-
Crack Tube	28	.31	5.1	-	-	-	-	-	-
Crack Weld	17	.19	3.1	-	-	-	-	-	-
"F" Fitting	20	.22	3.7	-	-	-	-	-	-

9,004 Returns
5,468,608 Operating Hours

Table A-2. Summary Matrix Composite Engine - All Engines (Continued)

Cause of Return	Necessary Number	Necessary (%)	Necessary Rate X10^6	Convenience Number	Convenience (%)	Convenience Rate X10^6	Total Number	Total (%)	Total Rate X10^6
Engine/ Component									
GP Turbine (All Causes)	37	.41	6.8	64	.71	11.7	101	1.12	18.5
Blades	34	.38	6.2	-	-	-	34	.38	6.2
Ret. Ring	3	.03	0.5	-	-	-	3	.03	0.5
PT Turbine (All Causes)	19	.21	3.5	6	.07	1.1	25	.28	4.6
Blades	3	.03	0.5	-	-	-	-	-	-
Gears	2	.02	0.4	1	.01	0.2	3	.03	0.5
Other	116	1.29	21.2	-	-	-	-	-	-
System Environ./Use									
FOD	1930	21.43	352.9	260	2.89	47.5	2190	24.32	400.5
Maintenance	297	3.30	54.3	27	.30	4.9	329	3.65	60.2
Erosion	786	8.53	140.4	71	.79	13.0	857	9.52	156.7
Corrosion	21	.23	3.8	7	.08	1.3	28	.31	5.1
Battle Damage	136	1.51	24.9	55	.61	10.1	191	2.12	34.9
Operator Error	56	.62	10.2	20	.22	3.7	76	.84	13.9
Airframe	18	.20	3.3				18	.20	3.3
Handling	16	.18	2.9	6	.07	1.1	22	.24	4.0
A/C Accident	350	3.89	64.0				350	3.89	64.0
Dirt				61	.68	11.2	61	.68	11.2

9,004 Returns
5,468,698 Operating Hours

Table A-3. Summary Matrix Composite Engine - All Military

Cause of Return	Necessary Number	Necessary (%)	Necessary Rate X10^6	Convenience Number	Convenience (%)	Convenience Rate X10^6	Total Number	Total (%)	Total Rate X10^6
Engine-Caused									
Seals (Mainshaft)	601	7.09	138.7	580	6.84	133.9	1181	13.94	272.6
Bearings									
(All Causes	455	5.37	105.0	56	.66	12.9	511	6.03	118
Race Rotation	115	1.36	26.5	-	-	-	-	-	-
Cage Failure	48	.57	11.1	-	-	-	-	-	-
Roller Defects	19	.22	4.4	-	-	-	-	-	-
Compressor									
(All Causes)	315	3.72	72.7	-	-	-	315	3.72	72.7
Blades	7	.08	1.6	-	-	-	-	-	-
Disc	239	2.82	55.2	-	-	-	-	-	-
Vanes	27	.32	6.2	-	-	-	-	-	-
Bolts	39	.46	9.0	-	-	-	-	-	-
Stators	4	.05	0.9	-	-	-	-	-	-
Air Diffuser									
(All Causes)	83	.98	19.2	-	-	-	83	.98	19.2
Crack Tubes	28	.33	6.5	-	-	-	-	-	-
Crack Weld	17	.20	3.9	-	-	-	-	-	-
"F" Fitting	20	.24	4.6	-	-	-	-	-	-

8,474 Returns
4,331,697 Operating Hours

Table A-3. Summary Matrix Composite Engine - All Military (Continued)

Cause of Return	Necessary Number	Necessary (%)	Necessary Rate X10^6	Convenience Number	Convenience (%)	Convenience Rate X10^6	Total Number	Total (%)	Total Rate X10^6
Engine-Caused									
GP Turbine									
(All Causes	34	.40	7.8	-	-	-	34	.40	7.8
Blades	32	.38	7.4	-	-	-	-	-	-
Ring	2	.02	0.5	-	-	-	-	-	-
PT Turbine	17	.20	3.9	-	-	-	17	.20	3.9
Blades	1	.01	0.2	-	-	-	-	-	-
Other	116	1.37	26.8	-	-	-	116	1.37	26.8
System Environ./Use									
FOD	1891	22.32	436.5	245	2.89	56.6	2136	25.21	493.1
Maintenance	285	3.36	65.8	13	.15	3.0	298	3.52	68.8
Erosion	736	8.69	169.9	65	.77	15.0	801	9.45	184.9
Corrosion	21	.25	4.8	7	.08	1.6	28	.33	6.5
Battle Damage	136	1.60	31.4	55	.65	12.7	191	2.25	44.1
Operator Error	54	.64	12.5	20	.24	4.6	74	.87	17.1
Airframe	13	.15	3.0	-	-	-	13	.15	3.0
Handling	16	.19	3.7	6	.07	1.4	22	.26	5.1
A/C Accident	289	3.41	66.7	-	-	-	289	3.41	66.7
Dirty Compressor	-	-	-	61	.72	14.1	61	.72	14.1

8,474 Returns
4,331,697 Operating Hours

Table A-4. Summary Matrix Composite Engine - Commercial
T5311 Series & T5313 Series

Cause of Return	Necessary			Convenience			Total		
	Number	(%)	Rate $X10^6$	Number	(%)	Rate $X10^6$	Number	(%)	Rate $X10^6$
Engine Caused									
Seal (Mainshaft)	22	3.49	19.4	14	2.22	12.3	36	5.71	31.7
Bearings									
(All Causes)	36	5.71	31.7	4	.63	3.5	40	6.35	35.2
Race Rotation	2	.32	1.8	-	-	-	-	-	-
Cage	7	1.11	6.2	-	-	-	-	-	-
Compressor	19	3.02	16.7	-	-	-	19	3.02	16.7
Disc	16	2.54	14.1	-	-	-	-	-	-
Vanes	3	.48	2.6	-	-	-	-	-	-
Air Diffuser	4	.63	3.5	-	-	-	4	.63	3.5
Power Shaft	2	.32	1.8	-	-	-	2	.32	1.8
PT Blades	2	.32	1.8	-	-	-	2	.32	1.8
GP Turbine	3	.48	2.6	-	-	-	3	.48	2.6
Ring, Blade Retaining	1	.16	0.9	-	-	-	1	.16	0.9
Sun Gear	1	.16	0.9	-	-	-	1	.16	0.9
Red. Gear	1	.16	0.9	-	-	-	1	.16	0.9
Vibration	1	.16	0.9	-	-	-	1	.16	0.9
GP Nozzle	-	-	-	5	.79	4.4	5	.79	4.4

630 Returns
1,136,911 Operating Hours

Table A-4. Summary Matrix Composite Engine - Commercial (Continued)
T5311 Series & T5313 Series

Cause of Return	Necessary			Convenience			Total		
	Number	(%)	Rate X10^6	Number	(%)	Rate X10^6	Number	(%)	Rate X10^6
System Environ./Use									
FOD	39	6.19	34.3	15	2.38	13.2	54	8.57	47.5
Maintenance	12	1.90	10.6	14	2.22	12.3	26	4.13	22.9
Erosion	50	7.94	44.0	6	.95	5.3	56	8.89	49.3
Operator Error	2	.32	1.8	-	-	-	2	.32	1.8
Airframe	5	.79	4.4	-	-	-	5	.79	4.4
A/C Accident	61	9.68	53.7	-	-	-	61	9.68	53.7
Overspeed	2	.32	1.8	-	-	-	2	.32	1.8
Administrative	-	-	-	18	2.86	15.8	18	2.86	15.8

630 Returns
1,136,911 Operating Hours

APPENDIX B
T53-L-13B ACTUARIAL ANALYSIS

ENGINES REMOVED TO DEPOT FOR ALL REASONS AND/OR CAUSES
FOR THE 18-MONTH PERIOD 1 JANUARY 1973 THROUGH 30 JUNE 1974

AGE INTERVAL (HOURS)	DEPOT RETURN RATE	% SURVIVING BEGINNING OF INTERVAL	% RETURNED IN INTERVAL	AGE INTERVAL (HOURS)	DEPOT RETURN RATE	% SURVIVING BEGINNING OF INTERVAL	% RETURNED IN INTERVAL
0-24	0.0300	100.00	3.00	900-924	0.0231	49.31	1.14
25-49	0.0190	97.00	1.84	925-949	0.0214	48.17	1.03
50-74	0.0174	95.16	1.66	950-974	0.0183	47.14	0.86
75-99	0.0152	93.50	1.42	975-999	0.0156	46.28	0.72
100-124	0.0140	92.08	1.29	1000-1024	0.0152	45.56	0.69
125-149	0.0149	90.79	1.35	1025-1049	0.0160	44.87	0.72
150-174	0.0174	89.44	1.56	1050-1074	0.0168	44.15	0.74
175-199	0.0194	87.88	1.70	1075-1099	0.0160	43.41	0.69
200-224	0.0194	86.18	1.67	1100-1124	0.0143	42.72	0.61
225-249	0.0182	84.51	1.54	1125-1149	0.0133	42.11	0.56
250-274	0.0185	82.97	1.53	1150-1174	0.0161	41.55	0.67
275-299	0.0206	81.44	1.68	1175-1199	0.0203	40.88	0.83
300-324	0.0227	79.76	1.81	1200-1224	0.0228	40.05	0.91
325-349	0.0236	77.95	1.84	1225-1249	0.0208	39.14	0.81
350-374	0.0228	76.11	1.74	1250-1274	0.0165	38.33	0.63
375-399	0.0212	74.37	1.58	1275-1299	0.0130	37.70	0.49
400-424	0.0205	72.79	1.49	1300-1324	0.0112	37.21	0.42
425-449	0.0211	71.30	1.50	1325-1349	0.0110	36.79	0.40
450-474	0.0207	69.80	1.44	1350-1374	0.0118	36.39	0.43
475-499	0.0196	68.36	1.34	1375-1399	0.0128	35.96	0.46
500-524	0.0192	67.02	1.29	1400-1424	0.0125	35.50	0.44
525-549	0.0195	65.73	1.28	1425-1449	0.0111	35.06	0.39
550-574	0.0203	64.45	1.31	1450-1474	0.0098	34.67	0.34
575-599	0.0204	63.14	1.29	1475-1499	0.0101	34.33	0.35
600-624	0.0192	61.85	1.19	1500-1524	0.0131	33.98	0.45
625-649	0.0175	60.66	1.06	1525-1549	0.0183	33.53	0.61
650-674	0.0170	59.60	1.01	1550-1574	0.0206	32.92	0.68
675-699	0.0184	58.59	1.08	1575-1599	0.0215	32.24	0.69
700-724	0.0200	57.51	1.15	1600-1624	0.0215	31.55	0.68
725-749	0.0208	56.36	1.17	1625-1649	0.0219	30.87	0.68
750-774	0.0199	55.19	1.10	1650-1674	0.0228	30.19	0.69
775-799	0.0175	54.09	0.95	1675-1699	0.0277	29.50	0.82
800-824	0.0158	53.14	0.84	1700-1724	0.0255	28.68	0.73
825-849	0.0165	52.30	0.86	1725-1749	0.0232	27.95	0.65
850-874	0.0196	51.44	1.01	1750-1774	0.0210	27.30	0.57
875-899	0.0223	50.43	1.12	1775-1800	1.0000	26.73	26.73

APPENDIX C

MAINTENANCE ALLOCATION CHARTS

SAMPLE
MAINTENANCE ALLOCATION CHART
FOR
T53-L-9A/11/11SA/11B/11C/11D/13A/13B/703

(1) GROUP NO.	(2) FUNCTIONAL GROUP	(3) MAINTENANCE FUNCTION: INSPECT	TEST	SERVICE	ADJUST	ALIGN	CALIBRATE	INSTALL	REPLACE	REPAIR	OVERHAUL	REBUILD	(4) TOOLS & EQUIPMENT	(5) REMARKS
03	Air Diffuser Housing	O[1]							D[3]	F				
	Rear Bearing Seal and Seal Housing	F[2]							F					
	Rear Bearing Seal Liner and Forward and Rear Cones	F							F					
	Impeller Housing	O							F	F				
	Compressor Housing	O							F	F				
	Compressor Stator Vanes	F							F	F				
	Compressor Rotor Blades	O*							F	F				*Visual inspect first stage
	Power Shaft	F							D					
	Inlet Housing	O							D	O*				*Corrosion control
	Air Inlet Vanes	O							D	F				
	Variable Inlet Guide Vane Assembly (T53-L-13A/13B/703)	O							D	F				
	Flow Divider and Dump Valve Assembly (T53-L-13A/13B/703)	O							O	O				
	Inlet Guide Vane Actuator Assembly (T53-L-13A/13B/703)	O			O				O		D			

SAMPLE

MAINTENANCE ALLOCATION CHART
FOR
T53-L-9A/11/11SA/11B/11C/11D/13A/13B/703

(1) GROUP NO.	(2) FUNCTIONAL GROUP	(3) MAINTENANCE FUNCTION INSPECT	TEST	SERVICE	ADJUST	ALIGN	CALIBRATE	INSTALL	REPLACE	REPAIR	OVERHAUL	REBUILD	(4) TOOLS & EQUIPMENT	(5) REMARKS
03	Inlet Guide Vane Actuator Hose (T53-L-13A/13B/703)	O							O					
	First- and Second-Stage Power Turbine Nozzle Assembly (T53-L-13A/13B/703)	F							F	F				
	Second-Stage Power Turbine Rotor Assembly (T53-L-13A/13B/703)	O*							F	F				*Visual Inspection
	First-Stage Power Turbine Rotor Assembly (T53-L-13A/13B/703)	F							F	F				
	First- and Second-Stage Gas Producer Rotor Assembly (T53-L-13A/13B/703)	F							F	F				
	First- and Second-Stage Gas Producer Nozzle and Flange (T53-L-13A/13B/703)	F							F	F				

SAMPLE
MAINTENANCE ALLOCATION CHART
FOR
T53-L-9A/11/11SA/11B/11C/11D/13A/13B/703

(1)	(2)	(3) MAINTENANCE FUNCTION											(4)	(5)
GROUP NO.	FUNCTIONAL GROUP	INSPECT	TEST	SERVICE	ADJUST	ALIGN	CALIBRATE	INSTALL	REPLACE	REPAIR	OVERHAUL	REBUILD	TOOLS & EQUIPMENT	REMARKS
03	Rear Bearing Aft Seal Housing (T53-L-13A/13B/703)	F							F					
	Rear Bearing Forward Seal and Forward Rear Oil Rings and Cones (T53-L-13A/13B/703)	F							F					
	Rear Bearing and Rear Bearing Housing (T53-L-13A/13B/703)	F							F					
	Rear Bearing Forward Seal and Forward Rear Oil Rings and Cones (T53-L-11 Series Engines)	F							D					
	Rear Bearing and Rear Bearing Housing (T53-L-11 Series Engines)	F							D					
	[1]O - Organizational													
	[2]F - Field													
	[3]D - Depot													

APPENDIX D

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS (FMECA)

SAMPLE

FAILURE MODE, EFFECTS AND CRITICALITY ANALYSIS

MATH MODEL NO	PART		POSSIBLE FAILURE				POSSIBLE FAILURE EFFECT		COMPENSATING FEATURES & REMARKS
	NUMBER	NAME	MODE	CAUSE	DURING	FREQ x 10-6	FUNCTIONAL SUBSYSTEM	ENGINE SYSTEM & CLASSIFICATION	
3.34 3.35	3-020-108-01 3-020-107-01	Nut & Locking Cup	Shear	Overtorque	A	1.9	Loss of pinch on inner race, possible rubbing of rotating parts and increased vibration levels.	Major Early stages result in metal chips in lubricating system, eventually leads to increased vibration and noise levels.	Large design safety factor. Cup is staked in two separate places to retain nut.
3.36	3-020-175-01	Gearshaft (Sungear)							
		Gear (Teeth)	Spalling	Fatigue	A	1.5	No immediate effect, eventually results in increased vibration.	Major No immediate effect on performance, but oil contamination results.	Early chip detection.
			Fracture	Fatigue	C	0.3	Increased vibration to loss of power transmission depending on number of teeth lost and the extent of secondary damage.	Major Increased noise and vibration levels, with possible loss of output torque depending on secondary damage.	Large design safety factor.
		Shaft	Fracture	Fatigue	C	0.2	Loss of power transmission.	L.O.C. Loss of output torque Turbine goes into overspeed condition.	Large design safety factor.
3.37	3-020-173-01	Gear (Teeth)	Spalling	Fatigue	A	1.5	No immediate effect, eventually results in increased vibration.	Major No immediate effect on performance, but oil contamination results.	Early chip detection.
		Gear (Teeth)	Fracture	Fatigue	C	0.3	Increased vibration to loss of power transmission depending on number of teeth lost and the extent of secondary damage.	Major Increased noise and vibration levels, with possible loss of output torque depending on secondary damage.	Large design safety factor.

APPENDIX E

ESTIMATING WEIBULL PARAMETERS FOR COMPONENT FAILURE MODES

Figures 26, 27, 28, and 35 in Section 1.0 are examples of Weibull plots made from historical engine data. A block of 300 newly fielded engines were monitored for component failure modes causing depot returns. Events were ranked and assigned median rank values for plotting points. Engines returned for causes other than the component failure mode under investigation were treated as suspensions. Since the engine data bank does not include component operating hours, new and not previously overhauled engines were selected to relate component hours to engine hours. A least-square line was fitted to the plotted points from which the characteristic life and slope were determined. Estimates derived by this method have the following weakness: Although the sample size is large, the number of actual plotted points is small, with a large number of suspended items. The components failure mode descriptions associated with field data events are frequently inadequate. Analysis of the Number 21 bearing showed that the skewing failure mode, which was eliminated by changing the roller breaker point radius, was also related to shaft alignment. The β of less than one is interpreted to mean that assemblies with misalignment would fail relatively early in time. With less misalignment, extended lives would occur, thus the slope of the Weibull least-square line is an indication of a decreasing failure rate.

The plot of the fourth-stage disc with a β of 1.2 is for the stress-rupture failure mode. The expected disc failure mode is cycle-dependent and should have a $\beta > 1$. However, the slope for this particular case may have been altered by high material temperatures.

The limitations described in analyzing the field data by the Weibull method are largely overcome when the method is applied to the results of component test data. Tests run to verify component integrity for low-cycle fatigue can yield important failure distribution data in a relatively short time by accelerated cycles or "murder" cycle testing.

The derivation of θ the characteristic life, from the B_{10} life for bearings is as follows:

The Weibull Reliability function:

$$R = e^{-\left(\frac{t}{\theta}\right)^{\beta}} \quad \text{or} \quad \frac{1}{e^{\left(\frac{t}{\theta}\right)^{\beta}}} \qquad (1)$$

Taking the natural log twice:

$$\ln R = \frac{1}{\left(\frac{t}{\theta}\right)^{\beta}} \quad \text{or} \quad -\ln R = \left(\frac{t}{\theta}\right)^{\beta}$$

$$\ln(-\ln R) = \beta \ln\left(\frac{t}{\theta}\right)$$

$$\ln\left(\frac{t}{\theta}\right) = \frac{\ln(-\ln R)}{\beta} \qquad (2)$$

let B_{10} life = t, 10 percent failing = R = ·1, .. R = ·9 substituting into (2)

$$\ln\left(\frac{B_{10}}{\theta}\right) = \frac{\ln(-\ln \cdot 9)}{\beta} = \frac{-2.25}{\beta}$$

$$\ln B_{10} - \ln \theta = \frac{-2.25}{\beta}$$

$$\ln \theta = \frac{2.25}{\beta} + \ln B_{10}$$

$$\theta = e^{\frac{2.25}{\beta}} \bullet B_{10}$$

APPENDIX F

STRESS-STRENGTH METHOD COMPONENT ANALYSIS

An analytical approach in the determination of the inherent reliability of the design is, for example, afforded through the use of a "stress-strength analysis" as follows:

Based on the random variables H and S, describing material strength and imposed stress, respectively, the reliability of a structural element may be defined as the probability that the material strength is greater than the imposed stress

or

$$R = P_r \ (H > S)$$

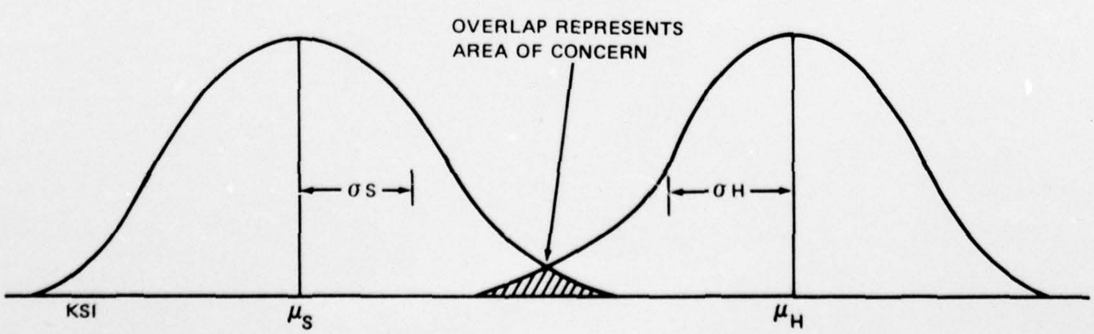
If H and S are normally distributed then

$$R = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z} e^{-\frac{x^2}{2}} dx = \phi \ (z)$$

where

$$Z = \frac{\mu_H - \mu_S}{\sqrt{\sigma_H^2 + \sigma_S^2}}$$

A pictorial representation of the above.



Therefore, strictly from this type of an analysis, a new design operating at an elevated temperature can have an equal reliability either by cooling, to keep the material operating temperature constant, and/or by a change to a material that presents the same strength characteristics.

This type of analysis, however, is subject to several uncertanties such as:

a. knowledge of the true imposed stress

b. when cooling is considered, the true material operating temperature

c. knowledge of the true material properties.

These uncertainties can be considerably reduced as a result of design and material selection philosophy and procedures coupled with test and field experience substantiating the techniques. The above method can be applied to compressors, combustors and turbines, in general, relative to low cycle fatigue, thermal fatigue, and derivatives such as stress-rupture and creep characteristics.